

## Modeling and Simulating Ultrasonic Wave Propagation in Layered Structures

1 March 1998

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13. ABSTRACT (Maximum 200 words)  Launch vehicles and spacecraft have many bonded layered structures, such as the propellant/insulation/case assembly in solid rocket motors, multilayered printed-circuit boards or solar array/composite panels in satellites. NonDestructive Evaluation (NDE) techniques are used to ensure bond integrity as part of standard quality assurance programs and/or to restore confidence when an unusual event occurs that may have compromised the hardware. Ultrasonic techniques are among the most common and powerful NDE techniques used to probe bond integrity; however, beyond a single layer, the signals can become very complex. This signal complexity often makes it difficult to determine inspection feasibility without performing expensive and time consuming tests on representative hardware samples with simulated flaws. Under the NDE MOIE program, a powerful, flexible, and user-friendly modeling program was developed using LabView™ to (1) simulate the propagation of ultrasonic waves through multilayered structures and (2) generate the oscilloscope signals one would expect to observe. In this report, the modeling program is described in detail, and sample results from a program simulation are compared with those of an associated experiment. The program's use of LabView™'s virtual instrument structure eases program modification/update and provides instant cross-platform compatibility. This simulation capability has already been utilized to support a number of programs, including Titan, Milstar and special programs.				
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## 1. Background

In the course of supporting many programs by evaluating inspection techniques, the NDE group has needed an analytical tool to model or simulate the propagation of ultrasonic waves through multi-layered structures. Launch vehicles and spacecraft have many bonded layered structures, such as the propellant/insulation/case assembly in solid rocket motors, multilayered printed circuit boards or solar array/composite panels in satellites. NonDestructive Evaluation (NDE) techniques are used to ensure bond integrity as part of standard quality assurance programs and/or to restore confidence when an unusual event occurs that may have compromised the hardware. Ultrasonic techniques are among the most common and powerful NDE techniques used to probe bond integrity; however, beyond a single layer, the signals can become very complex as the number of echoes grows with the sound waves reverberating in each layer, and the reverberations spawning additional echoes in other layers. This signal complexity often makes it difficult to determine inspection feasibility without performing expensive and time consuming tests on representative hardware samples with simulated flaws. A computer model/simulation, however, provides initial feasibility evaluation at a low cost and in a timely manner. Additionally, the model is a valuable tool for interpreting complex ultrasonic signals in the laboratory and in the field. The "1D Multilayer UT Model" was developed under the NDE MOIE program to address these needs.

"1D Multilayer UT Model" was written in LabView™ and is a powerful, flexible, and user-friendly program. The program allows one to simulate the propagation of ultrasonic waves through multi-layered structures and provides user feedback through real-time display of waves in the layers and the oscilloscope trace that one would expect to observe. In this report, the Physical Model section describes the physical principles behind the program; the Architecture section discusses the logic employed; the Verification section compares simulation results with laboratory experiment; and the Using the Program section describes the user interface. Detailed documentation for the LabView™ virtual instruments is provided in the appendix.

## 2. Physical Model

A layered structure can be inspected by using a transducer to send sound waves through a coupling medium in contact with the top layer; see left side of Figure 1. As the sound travels through the structure, portions of the sound energy are transmitted or reflected at each interface. In a pulse-echo technique, the sound reflected back to the top surface is detected by the original sending transducer. In the alternative through-transmission technique, a second transducer on the opposite side detects the sound transmitted through the entire structure. In either case the system in general can be treated analytically as  $n$  layers sandwiched between top and bottom semi-infinite layers. The simplifications assumed in this model are the following:

1. The layers are flat and parallel.
2. The waves travel normal to the interfaces. At an interface a wave will be reflected and transmitted, but not mode converted.
3. The material in each layer is uniform; i.e., the ultrasonic wave does not interact with microstructure in a material other than what is accounted for by the general attenuation.
4. Dispersion; i.e., the different frequency components of the wave propagating at different velocities and attenuations, is **not** included.
5. Beam spread is **not** included, although, to some degree, it can be factored into the attenuation.

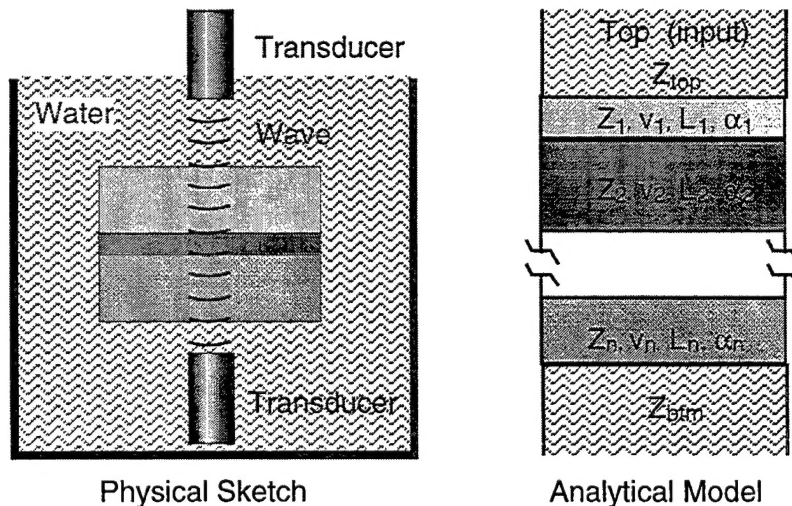


Figure 1. The physical sketch on the left shows a typical ultrasonic inspection of a three-layer structure with water as the coupling medium. The analytical model, on the right, is generalized to  $n$  layers sandwiched between top and bottom semi-infinite layers.

As the ultrasonic wave propagates, two methods will be considered to modify the wave—(1) the general attenuation of the isotropic uniform material, and (2) the interaction at an interface. The wave's pressure amplitude is attenuated as the wave travels through a material a distance  $d$  by a factor of  $e^{-\alpha d}$ , where  $\alpha$  is the material's attenuation coefficient in neepers/mm or Np/mm. Note, the attenuation is also commonly given in units of dB/mm, and  $1 \text{ Np/m} = 8.686 \text{ dB/m}$ . Typical attenuation factors are  $\sim 5 \text{ dB/m}$  for Al and  $2.2 \text{ dB/mm}$  for water at  $1 \text{ MHz}$  and  $25^\circ\text{C}$ .

The interaction at an interface results in the wave energy partitioning into a reflected wave and a transmitted wave; see Figure 2. The amplitudes of these waves are determined by the reflection coefficient,  $R_{n,n+1}$ , and transmission coefficient,  $T$ . These coefficients depend on the two acoustic impedances of the layers,  $Z_n$  and  $Z_{n+1}$ . For the interface between layer  $n$  and layer  $n+1$ , the coefficients are the following:

$$R = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n} ; \quad T = \frac{2Z_{n+1}}{Z_{n+1} + Z_n} .$$

The waves are separated into two arrays; i.e., the forward traveling wave and the reverse traveling wave. In accordance with the superposition principle, the total sound wave in a layer is just the sum of the forward and reverse waves or arrays in this case.

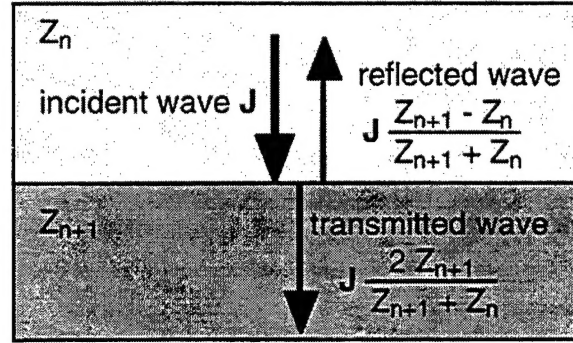


Figure 2. The interaction at an interface between the  $n$  and  $n+1$  layer with acoustic impedances, respectively, of  $Z_n$  and  $Z_{n+1}$ .

### 3. Architecture

#### 3.1 Overview

To run a simulation, the user enters acoustic and geometric parameters, and required resolutions. The program then proceeds to do the following: (1) calculate the array dimensions; (2) request input waveform information (at users option); (3) propagate the waves until the user presses the stop button or pause button; and (4) display or save to a file the wave in any layer and/or the scope outputs

#### 3.2 Inputs and Outputs

The inputs and outputs are shown schematically in Figure 3. The user selects the number of layers between semi-infinite top and bottom layers (Figure 1). The required input parameters for each layer are the acoustic impedance,  $Z_n$ ; the velocity,  $v_n$ ; the path length in layer,  $L_n$ ; and the attenuation,  $\alpha_n$ . Material parameter inputs also include the impedance of the medium from which the wave is input into the first layer,  $Z_{top}$ , and the impedance of the medium in contact with the last layer,  $Z_{btm}$ . The user selects the input wave's frequency and shape parameters, or, alternatively, manually inputs an arbitrary wave. The outputs include displays of the waves propagating in individual layers and the signals that would be received in pulse-echo or through-transmission techniques. The program's received signal displays are called Top Scope and Bottom Scope since in inspection the signals are displayed on an oscilloscope or scope. The Top Scope is the pulse-echo signal, and the Bottom Scope is through-transmission signal.

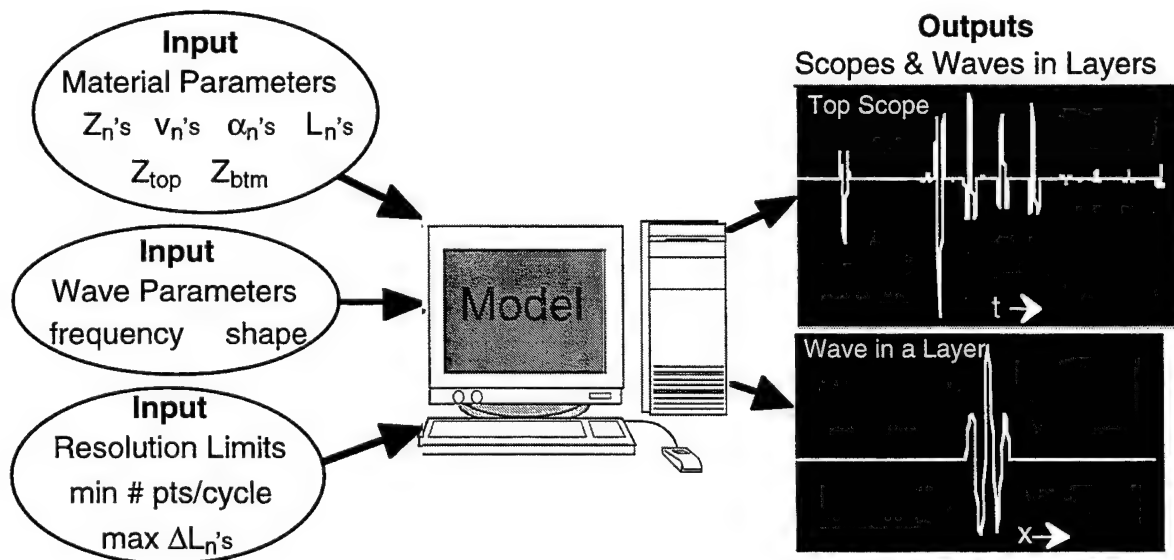


Figure 3. Schematic of program's inputs and outputs.

### 3.3 Arrays and Array Dimensioning

The program uses a number of arrays see Table 1. The arrays are either user input values, internal calculation arrays, or output value arrays. As mentioned earlier, sound waves are moving in the forward and the reverse directions, and separate arrays are set up in each layer for each direction; see Figure 4. The dimensioning of the layers' wave arrays is dependent on the input wave's frequency,  $f$ , the  $v_n$ 's,  $L_n$ 's, and  $\max\Delta L_n$ 's. The input wave has  $i$  points per cycle, and a time between points,  $\Delta t = 1/(f i)$ . The  $n^{\text{th}}$  layer's arrays have the number of points,  $k_n$ , calculated with the expression,

$$k_n = \text{Integer}\left(\frac{L_n}{v_n \Delta t}\right).$$

However, to satisfy the user's input resolution limits, the  $k_n$ 's and  $i$  are calculated by an iterative process. Initially,  $i$  is set to the  $i_{\min}$  input by user, and the  $k_n$ 's are calculated. If the condition of  $(L_n / k_n) \leq \max\Delta L_n$  (recall the  $\max\Delta L_n$ 's are user inputs) is not satisfied for all  $n$ 's, then  $i$  is increased until the condition is met for all  $n$ . Following the calculation of  $k_n$ 's, the Prop/el array is calculated. This array is the propagation attenuation factor; i.e.  $\text{Prop/el}_n = \exp(-\alpha_n \Delta L_n)$ . The TopScope and BtmScope arrays' dimensions are open-ended and grow with each iteration, i.e.,  $\Delta t$ , of the model.

Table 1. Arrays used in model.

Array Type	Array Name	Description
User Input	Z	$Z_n$ , material input impedances
	velocity	$v_n$ , material velocities
	Atten dB/mm,	$\alpha_n$ , material attenuation coefficients
	Length,	$L_n$ , path lengths
	$\Delta L_{\max}$	$\max\Delta L_n$ , maximum path differences
Internal Calculation (significant ones)	Input Wave	Input Wave
	FwdWvs	Forward Waves for all layers
	RevWvs	Reverse Waves for all layers
	pts/layer	points in each layer, $k_n$
	RefTop	$R_{n,n-1}$ at the top interface of the $n$ th layer
	RefBtm	$R_{n,n+1}$ at the bottom interface of the $n$ th layer
	Prop/el	propagation values calculated from $\alpha_n$ s
Out Arrays	LayersWvs	equal to FwdWvs+ RevWvs
	TopScope	output signal from top layer
	BtmScope	output signal from bottom layer



### 3.4 Propagating the Waves (i.e., Cycling Model One Iteration)

One iteration of the model corresponds to time being incremented by  $\Delta t$ , and the waves in every layer advancing one element. The complex process of iterating the model once in the pulse mode is diagrammed in Figure 4 and described by the following array operations:

#### 1. Input Wave Array

- a. The  $i^{\text{th}}$  element is sent to layer 1's forward wave. All other elements moved forward one element, and a zero is put in the 1<sup>st</sup> element.

#### 2. Layer 1, Forward Wave Array

- a. The  $m^{\text{th}}$  element ( $m < k_1$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_1}$ , and moved to the  $m+1$  element.
- b. 1<sup>st</sup> element is set to sum of the  $i^{\text{th}}$  element from Input Wave and the reflected part from 1<sup>st</sup> layer's reverse wave.
- c. The original  $m = k_1$  element is multiplied by the reflection coefficient and sent to the 1<sup>st</sup> layer's reverse wave and multiplied by transmission coefficient and sent to 2<sup>nd</sup> layer's forward wave.

#### 3. Layer 1, Reverse Wave Array

- a. The  $m^{\text{th}}$  element ( $m > 1$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_1}$ , and moved to the  $m-1$  element.
- b. The  $k_1^{\text{th}}$  element is set to sum of the transmitted part from the 2<sup>nd</sup> layer's reverse wave and the reflected part from 1<sup>st</sup> layer's forward wave.
- c. The  $m = 1$  element is (1) multiplied by the reflection coefficient and sent to the 1<sup>st</sup> layer's forward wave and (2) multiplied by transmission coefficient and added to TopScope array.

#### 4. Layer $j$ with $1 < j < n$ , Forward Wave Array

- a. The  $m^{\text{th}}$  element ( $m < k_j$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_j}$ , and moved to the  $m+1$  element.
- b. 1<sup>st</sup> element is set to sum of the transmitted part from the  $j-1$  layer and the reflected part from this layer's reverse wave.

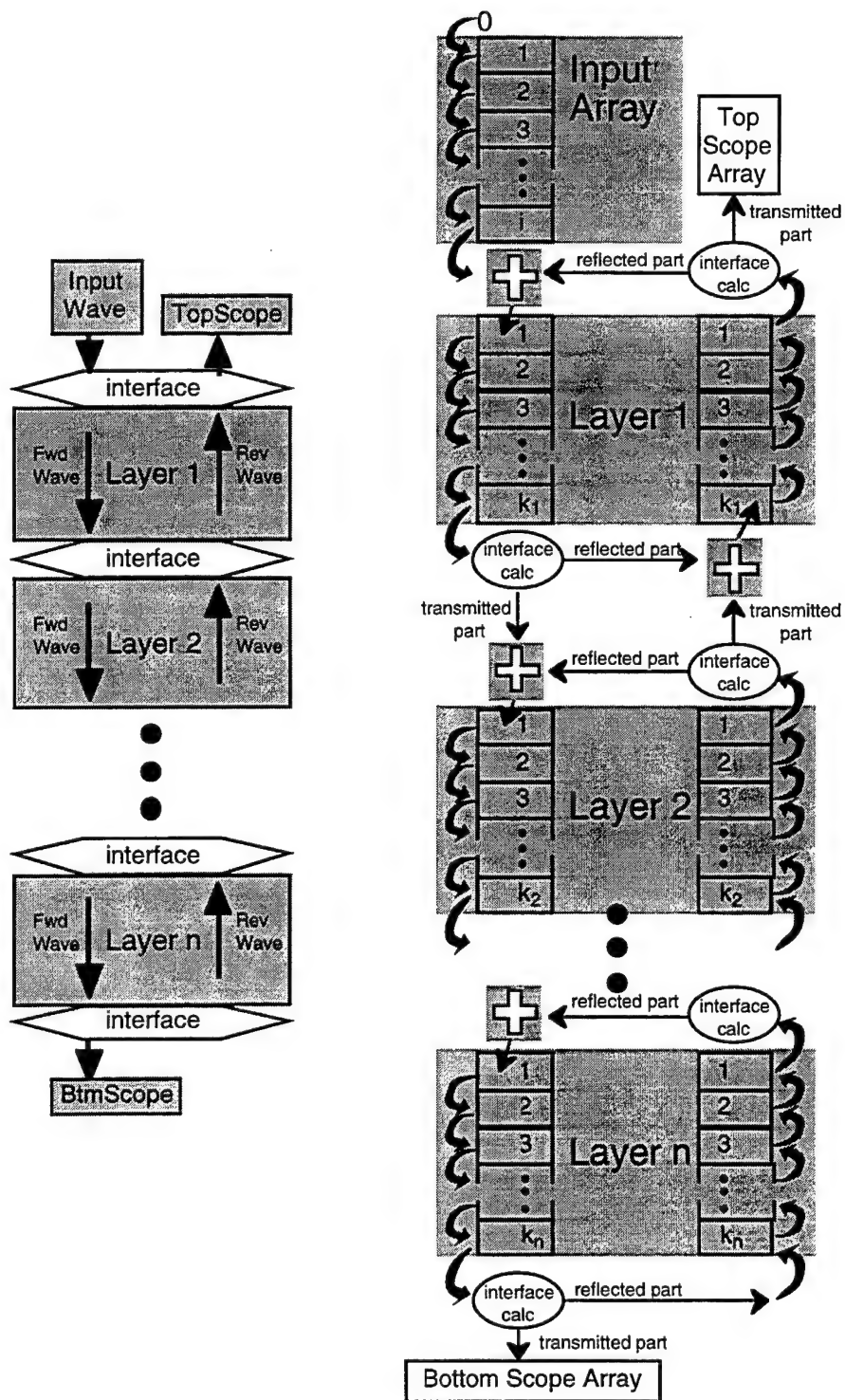


Figure 4. On the left is a general schematic showing the wave propagation and interactions in the model. On the right are the details of the processes involved in iterating the model once and moving the waves (i.e., arrays) one  $\Delta t$ .

- c. The original  $m = k_j$  element is (1) multiplied by the reflection coefficient and sent to this layer's reverse wave and (2) multiplied by transmission coefficient and sent to layer  $j+1$ 's forward wave.

#### 5. Layer $j$ with $1 < j < n$ , Reverse Wave Array

- a. The  $m^{\text{th}}$  element ( $m > 1$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_j}$ , and moved to the  $m-1$  element.
- b. The  $k_j$ th element is set to sum of the transmitted part from the  $j+1$  layer's reverse wave and the reflected part from this layer's forward wave.
- c. The  $m = 1$  element is (1) multiplied by the reflection coefficient and sent to this layer's forward wave and (2) multiplied by transmission coefficient and sent to the  $j-1$  reverse wave.

#### 6. Layer $n$ (last layer), Forward Wave Array

- a. The  $m^{\text{th}}$  element ( $m < k_n$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_n}$ , and moved to the  $m+1$  element.
- b.  $1^{\text{st}}$  element is set to sum of the transmitted part from the  $n-1$  layer and the reflected part from this layer's reverse wave.
- c. The original  $m = k_n$  element is (1) multiplied by the reflection coefficient and sent to this layer's reverse wave and (2) multiplied by transmission coefficient and added to the BtmScope array.

#### 7. Layer $n$ (last layer), Reverse Wave Array

- a. The  $m^{\text{th}}$  element ( $m > 1$ ) is multiplied by the attenuation factor,  $\text{Prop}/e_{l_n}$ , and moved to the  $m-1$  element.
- b. The  $k_n$ th element is set to the reflected part from this layer's forward wave.
- c. The  $m = 1$  element is (1) multiplied by the reflection coefficient and sent to this layer's forward wave and (2) multiplied by transmission coefficient and sent to the  $n-1$  reverse wave.

#### 4. Verification

The program was experimentally verified with a simple three-layer system of polystyrene, water, and aluminum in a water immersion tank, Figure 5. A Panametrics 5052PRX pulser/receiver (SN:1482) was used in pulse-echo mode with a Panametrics 20-MHz, 0.25-in. transducer (V317/SN:189384). The waveforms were recorded with a Tektronix 720 digital oscilloscope (SN:B011318) at a digitization rate of 500 Msamples/s and transferred to an Apple Macintosh Quadra 950 for graphing.

The program was run using the physical parameters in the table in Figure 5 and with an input waveform of 17.5 Mhz (the transducer's measured frequency), 6 half cycles, and a Gaussian shape factor of 4.5. The overall comparison in Figure 6 shows very good agreement of the simulation with experiment. The echoes are all at the right times, and the amplitudes in the early times are consistent. The later time amplitudes of the experiment are smaller, which is consistent with beam spread that is not currently accounted for in the program. The simulation shows a very small echo at about 24.2  $\mu$ s, which isn't apparent in the experiment in Figure 6. However, the echo is observable in the experimental data at higher magnification. The difference in amplitude is probably due to the standard "book" values of impedance and attenuation used in the simulation being slightly off from the properties of the experiment's materials. The magnified portion of the waves in Figure 7 illustrates the program's accurate phase reproduction. The phase flips on the center echo in both model and experiment.

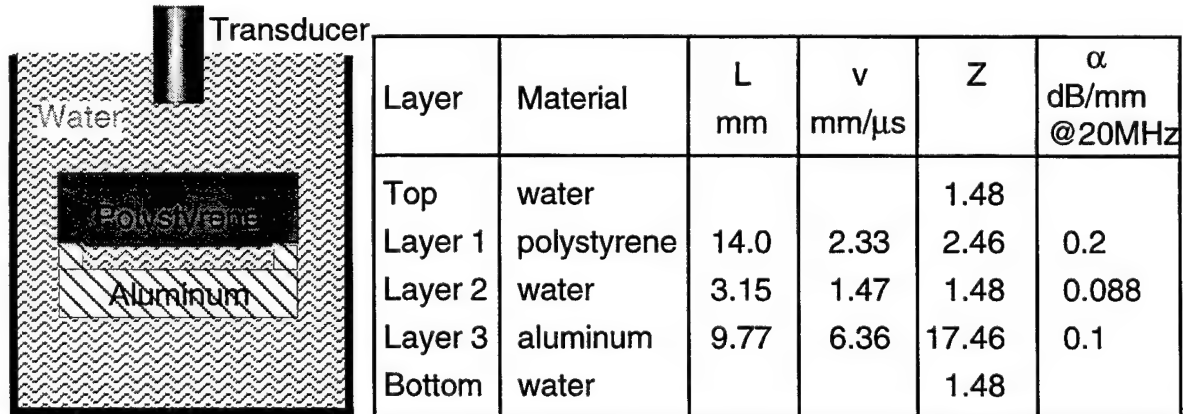


Figure 5. The verification experimental arrangement. The velocity, impedance, and attenuation values are from the literature.

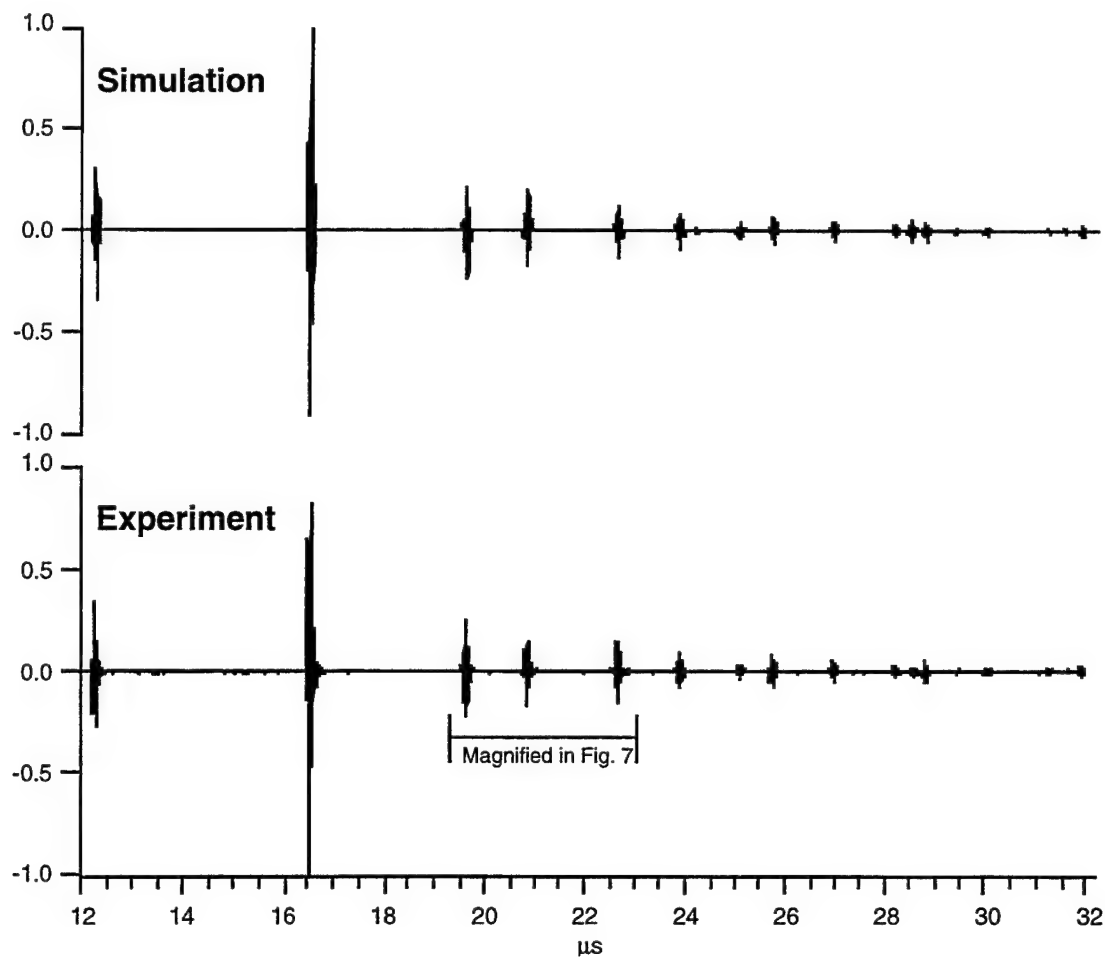


Figure 6. The top waveform is the Topscope trace generated by the ultrasonic model. It is in very good agreement with the scope trace from the pulse-echo experiment below. In the experiment, as the wave travels farther, beam spread becomes a significant factor in attenuating the signal and is not accounted for in the model.

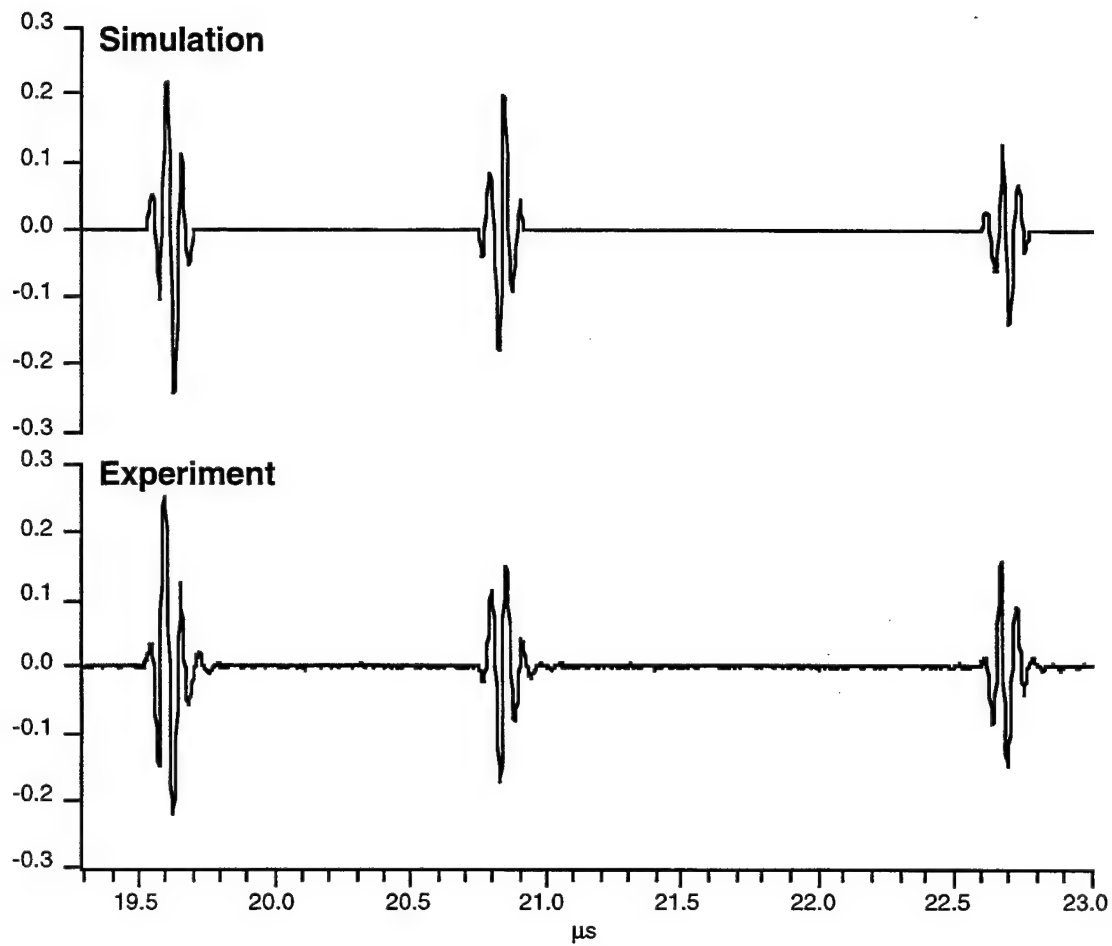


Figure 7. Magnified region of Fig. 6. The phase of the model's simulated signal matches that of the experiment as seen in the phase flip of the reflected signal at  $\sim 20.8 \mu\text{s}$ .

## 5. Using the Model

### 5.1 Overview

The major goals in the interface design were (1) ease of use, (2) maximum flexibility, and (3) efficient use of screen space for use on small laptops. The virtual instrument (vi) panels are laid out in a compact logical format with liberal use of color cues. The controls and inputs have detailed description information accessible in the LabView™ Help window. The user has full real-time control of what results are displayed and saved. The small and separate windows for graphs and controls make the program laptop friendly.

### 5.2 Inputting Parameters

The 1D Multilayer UT Model vi's control panel, Figure 8, is the primary method of entering information and accessing the displays and secondary controls. Many of the values have associated physical units; e.g., velocity has units mm/μs. The user is not restricted to the default units in displaying or entering data. The units may be changed by typing in a consistent unit; e.g., in/s can be used instead of mm/μs. LabView™ automatically converts and keeps track of the units in operations.

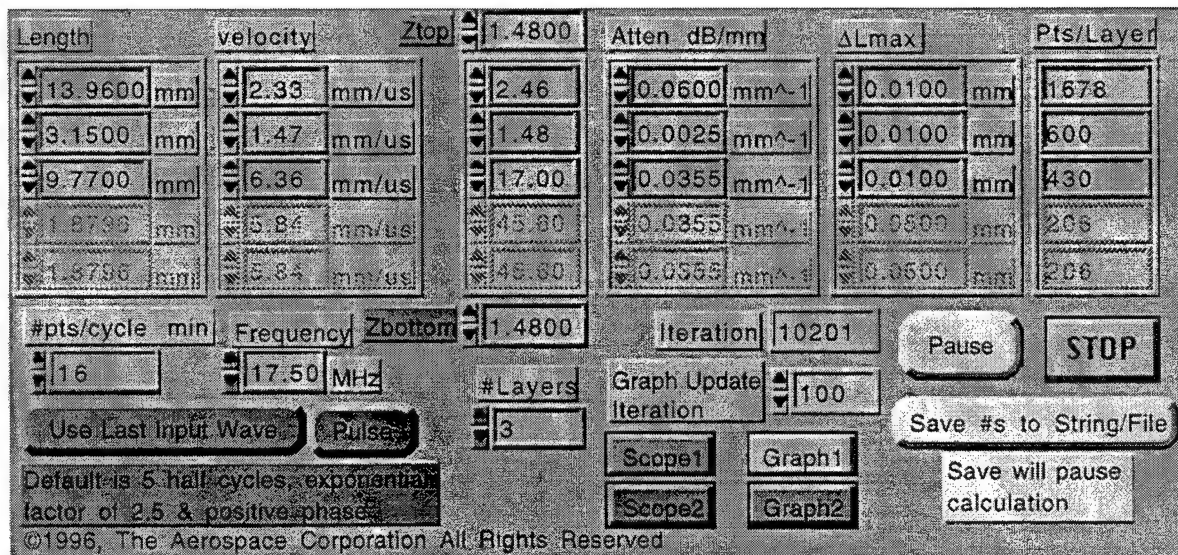


Figure 8. The 1D Multilayer UT Model vi's control panel serves as the program's main interface for control and information input.

Prior to running a simulation, the following information is entered: (1) the geometric and acoustic parameters for the layers; (2) the resolution parameters— $\Delta L_{\max}$  for each layer and #pts/cycle min; (3) the number of layers; (4) input wave frequency; (5) select pulse or continuous input wave; and (6) select default input wave or modify input wave. The last two entries are selected by buttons on the panel.

If the choice was made to modify the input wave, the program pops up WaveInput vi's panel, Figure 9, after the program starts running. This vi either generates an input waveform using the waveshape parameters input into the program or accepts an arbitrary wave input point by point. The input generation parameters include the number of half cycles, a Gaussian exponential shape factor, and positive/negative phase. The result of a parameter change is immediately observed in the waveform graph. Following generation of an acceptable input wave, pressing the "DONE" button exits WaveInput vi, and the program begins to wave propagation.

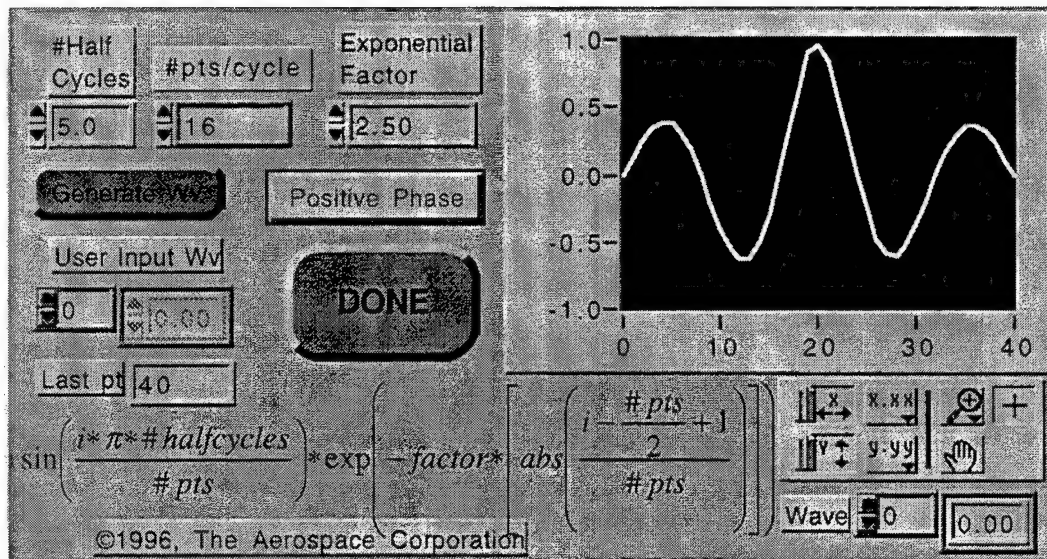


Figure 9. The input wave's shape is controlled using the WaveInput vi's panel.



The wave in a layer or oscilloscope output can be displayed at any time during the propagation operation. The display vi's can be opened by pressing a button on the 1D Multilayer UT Model vi's panel or from a pull-down menu. A layer wave is displayed by a LayerGraph vi panel, Figure 10, and an oscilloscope signal is displayed in a UTScope vi panel, Figure 11. In the LayerGraph vi panel, the layer number control selects which layer's wave is displayed. The unit button changes the distance units between millimeters and inches. In the UTScope vi panel, a button is used to select pulse-echo or through transmission signal for display. The display panels have on-off buttons since turning off the graph displays can dramatically speed the propagation operation.

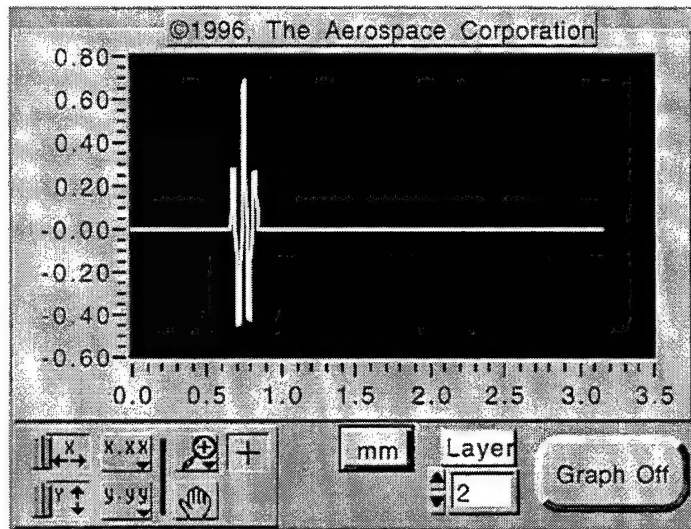


Figure 10. The wave in a layer is displayed using the LayerGraph vi's panel. The layer number control selects which layer's wave is displayed. The unit button changes the distance units between millimeters and inches.

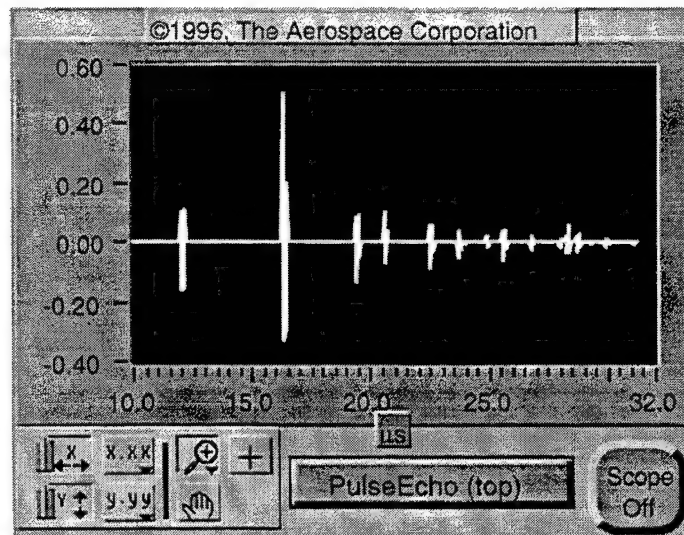


Figure 11. The pulse-echo or through-transmission oscilloscope signal is displayed in a UTScope vi panel.

Pressing the “Save #s to String/File” button brings up the Save #s Strg/File vi panel, Figure 12. The wave for any layer and scope outputs can be saved to files. The file format is selected by menu and includes Igor binary format in addition to several ASCII text formats. The scope outputs may also be displayed in a string format to allow copy and paste to another application for analysis via clipboard.

The program will propagate the waves until the “Stop” button is pressed. All the waves are still in memory even after the “Stop” button is pressed and can be saved by running the Save #s Strg/File vi. During the program operation, the scope arrays each grow by one point for each iteration, thus the program will eventually run out of memory if left running open ended. Currently, the program has minimal error checking and has no alerts for a potential out of memory condition.

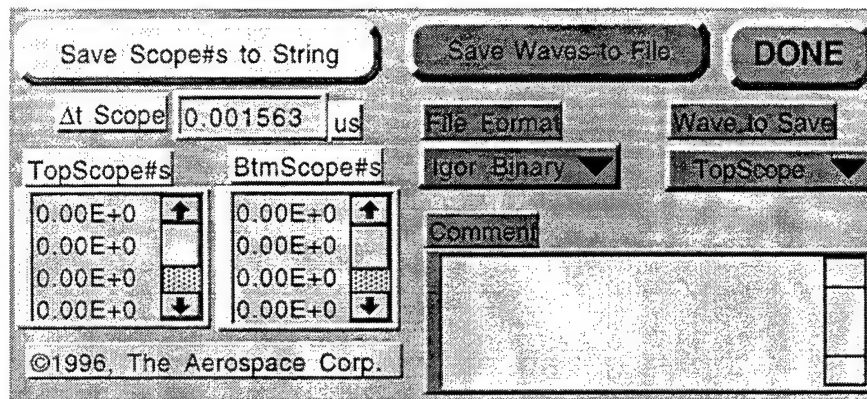


Figure 12. The waves are saved with the Save #s Strg/File vi.

## 6. Conclusions and Comments

The 1D Multilayer UT Model was verified with experiment to provide accurate simulation of oscilloscope outputs. The LabView™ programming language has eased the modification process during development and is expected to ease the process in future modifications and the addition of new features. The program was ported from Macintosh to PC environment by simply copying the vi's to the PC and opening them under LabView™ for Windows.

On the drawing board are a few minor changes to the program to improve the ease of use. These include the following: (1) expand the WaveInput wave generation options and improve the arbitrary wave input interface; (2) enhance the error checking; (3) expand the number file formats for saved wave data, and (4) add a beam-spread algorithm. A more detailed manual is planned that will document some of the convenient features not in this report, such as the little database vi that contains many common materials' acoustic properties.

## **Appendix**

### **1D Multilayer UT Model's Virtual Instruments LabView™ Documentation**

## THE MAJOR VIRTUAL INSTRUMENTS' FUNCTIONS

Top Level vi



1D MultiLayer Model

Set-up initial condition vi's



Cal Arrays' SizesModel



WaveInputl.vi

Propagation vi's



1layer move wvs 1elem.vi



Interface Reconcvile.vi

Output vi's



UTLayerGraph



UTScope



Wave #s to Strg/file

Variables vi



Global.vil

Database vi



Acoustic Properties



## 1D MultiLayer Model

Last modified on 10/7/96 at 3:20 PM

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## Connector Pane



## Q540ppcHD:LabVIEW4ppc:UTModel2.llb:1D MultiLayer Model

V1.0, 6 August 1996 by Jim Lhota. Ultrasonic 1D finite element model for wave propagation through multilayer stack of materials. Created by Jim Lhota based on my previous 2 layer model. The number of layers is limited currently to 255, but can easily be increased by changing from U8 integer to U16 or U32 integer.

## Front Panel

Length	velocity	Ztop	Atten dB/mm	ΔLmax	Pts/Layer	ArrIndx	RelBtm	RefTop	PropRel	Prop n <sub>n+1</sub>
13.9600 mm	2.33 mm/us	2.46	0.0380 mm <sup>-1</sup>	0.0100 mm	1917	0	-0.2487	-0.2487	1.0000	1.0000E+0
3.1500 mm	1.47 mm/us	1.48	0.0025 mm <sup>-1</sup>	0.0100 mm	686	1917	0.8398	0.2487	1.0000	9.9998E-1
9.7700 mm	6.36 mm/us	17.00	0.0355 mm <sup>-1</sup>	0.0100 mm	492	2603	-0.8398	-0.8398	0.9999	9.9998E-1
1.2700 mm	5.84 mm/us	22.50	0.0355 mm <sup>-1</sup>	0.0500 mm	306	226	0.0500	0.0000	0.5000	0.0000E+0
1.2700 mm	5.84 mm/us	22.50	0.0355 mm <sup>-1</sup>	0.0500 mm	306	226	0.0500	0.0000	0.5000	0.0000E+0

#pts/cycle min: 16 Frequency: 20.00 MHz #Layers: 3

Iteration: 94 Graph Update Iteration: 100

Buttons: Pause, STOP, Save #s to String/File, Save will pause calculation

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## Controls and Indicators

**Ztop**

Acoustic Impedance of the semi-infinite medium above the first layer -  $(\text{mm}/\mu\text{s}) \cdot (\text{g}/\text{cm}^3)$  or  $0.001 \cdot \text{g}/(\text{mm}^2 \mu\text{s})$  or  $(10^6) \cdot \text{kg}/(\text{m}^2 \text{s})$

**Zbottom**

Acoustic Impedance of the semi-infinite medium below the last layer -  $(\text{mm}/\mu\text{s}) \cdot (\text{g}/\text{cm}^3)$  or  $0.001 \cdot \text{g}/(\text{mm}^2 \mu\text{s})$  or  $(10^6) \cdot \text{kg}/(\text{m}^2 \text{s})$

**Length**

Thickness of each layer, i.e. path length.

**L1**

**velocity**

Velocity of each layer.

**Z**

Acoustic Impedance of each layer --  $(\text{mm}/\mu\text{s}) \cdot (\text{g}/\text{cm}^3)$  or  $0.001 \cdot \text{g}/(\text{mm}^2 \mu\text{s})$  or  $(10^6) \cdot \text{kg}/(\text{m}^2 \text{s})$

**Atten dB/mm**

Attenuation coefficient of each layer.



## 1D MultiLayer Model

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[SGL]

[SGL]

 **$\Delta L_{max}$** Limits of maximum size of an element in each layer.  $\Delta L_{max} \geq \text{Length}/\#pts$ .

[SGL]

[U16]

**#pts/cycle min**

Minimum pts in a wavelength.

[TF]

**CW/Pulse**

Pulse - the waveform is input followed by zeros.

Continuos - the waveform is repetively input (note: for continuos use an even number of cycles)

[SGL]

**Frequency**

[TF]

**WvInput Ctl**

Brings up "WaveInput.vi" control panel to set wave parameters.

[U16]

**Graph Update Iteration**

[TF]

**stop**

Stops the calculation and exits. Note after stopping the last data is still in the global.vi and can be saved by running the subVI "Save #s to Strg/File"

[TF]

**Pause**

[U8]

**#Layers**

The number of layers to be used in calculation. Other layers will be ignored.

[TF]

**Save Waves**

[TF]

**Scope1**

[TF]

**Scope2**

[TF]

**Graph1**

[TF]

**Graph2**

[U16]

**Pts/Layer**

Number of elements that each layer is divided into for calculation.

[U16]

[U16]

**Iteration**

[SGL]

**RefBtm**Calculated reflection coefficient at the bottom of layer  $n = (Z_{n+1} - Z_n)/(Z_{n+1} + Z_n)$ . Note for last layer  $Z_{n+1} = Z_{bottom}$ 

[SGL]

[SGL]

**RefTop**Calculated reflection coefficient at the bottom of layer  $n = (Z_n - Z_{n-1})/(Z_n + Z_{n-1})$ . Note for first layer  $Z_{n-1} = Z_{top}$ .

[SGL]

[SGL]

**Prop/el**Propagation coefficient between elements in each layer. Calculated from attenuation coefficient. Note this value is  $\leq 1$ , e.g. if no attenuation the whole signal is propagated and the value would be 1.

[SGL]



## 1D MultiLayer Model

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**[U16] ArrIndx**

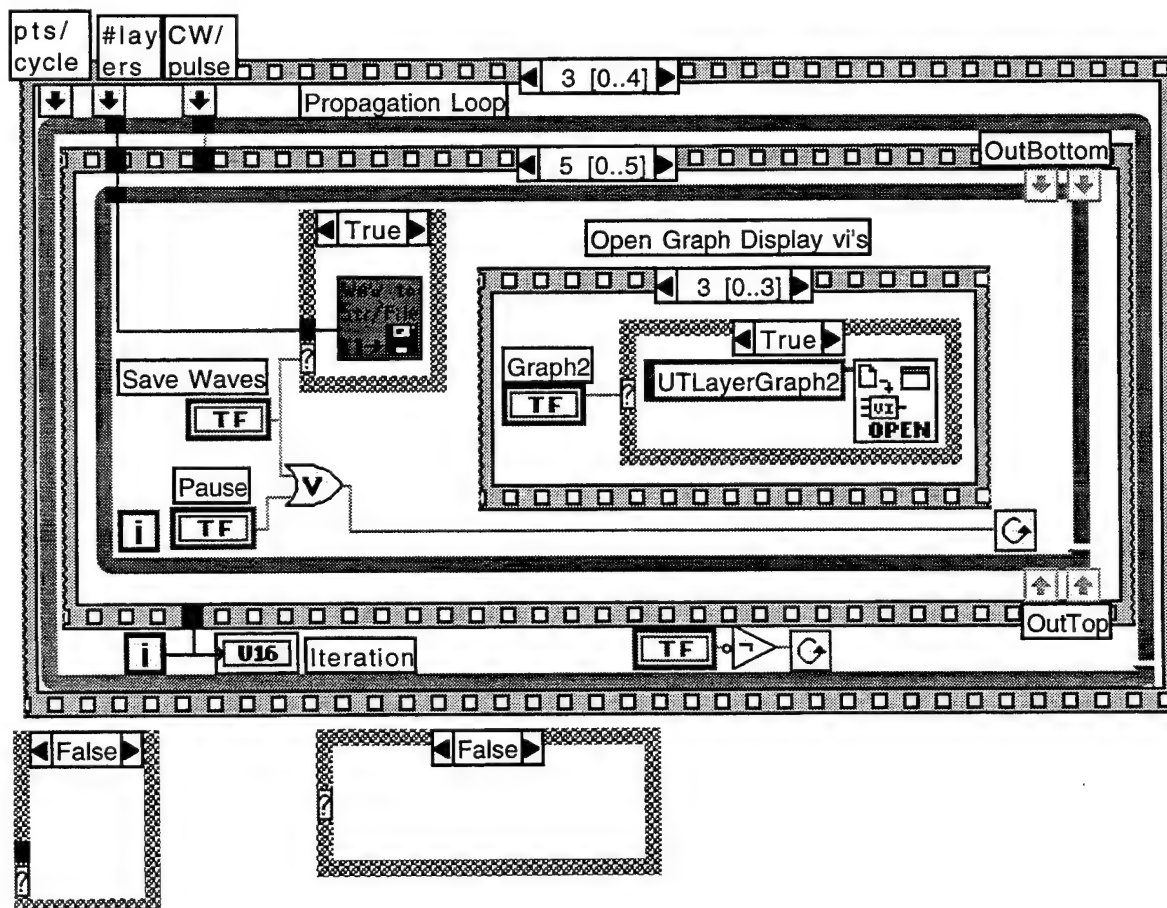
The waves for all layers are in two giant arrays (WvsFwd & WvsRev) and this index is where each layers waves start in these arrays.

**[U16]****[SQL] WvsFwd****[SQL]****[SQL] WvsRev****[SQL]****[U16] LastPtInWv****[SQL] Prop n\_n+1**

Propagation coefficient between elements between layer n and n+1 based on the attenuation coefficient and not to be confused with the transmission coefficient from the impedance. Note this value is  $\leq 1$ , e.g. if no attenuation the whole signal is propagated and the value would be 1.

**[SQL]****[SQL] Input Wv****[SQL]**

## Block Diagram



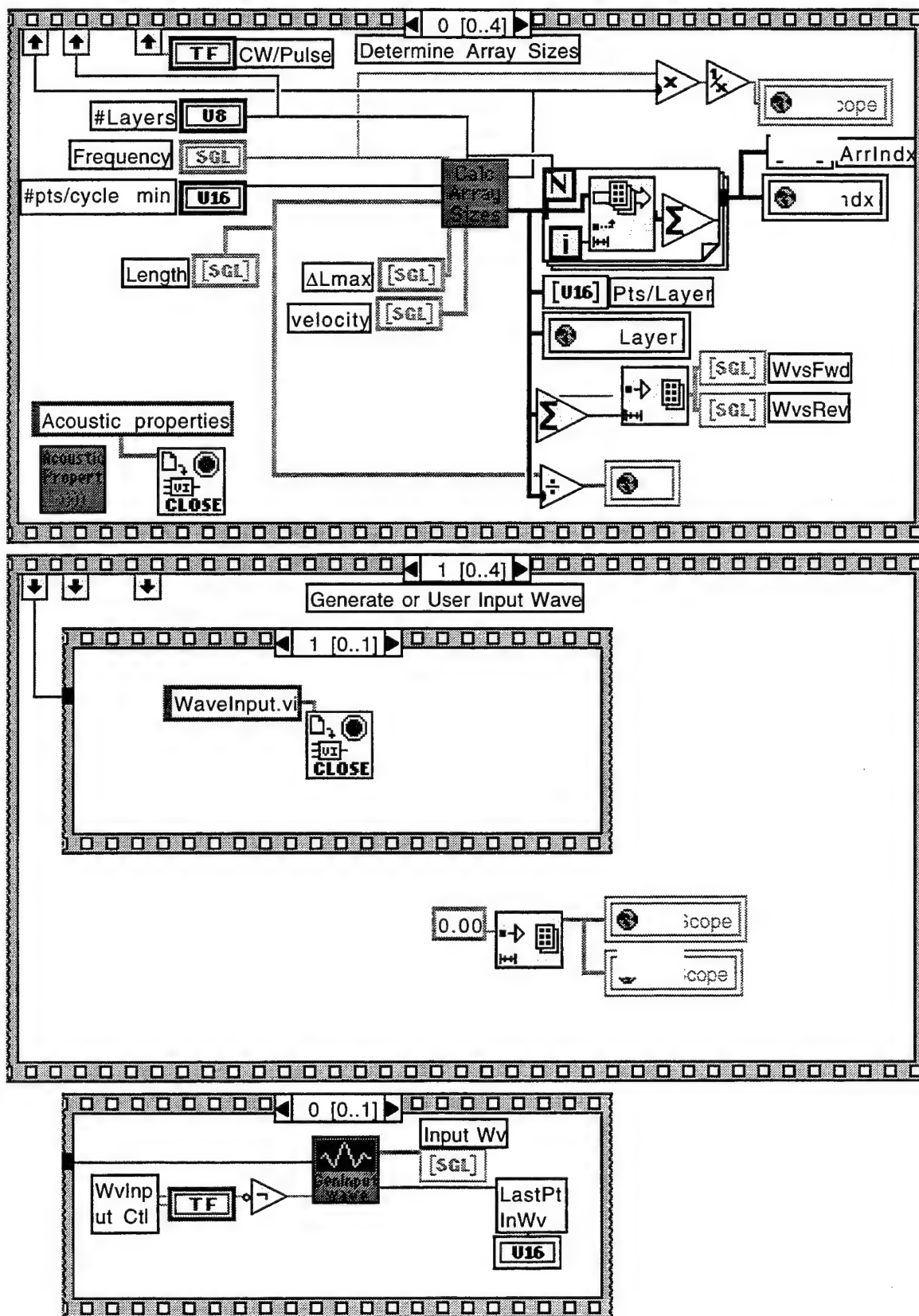




# 1D MultiLayer Model

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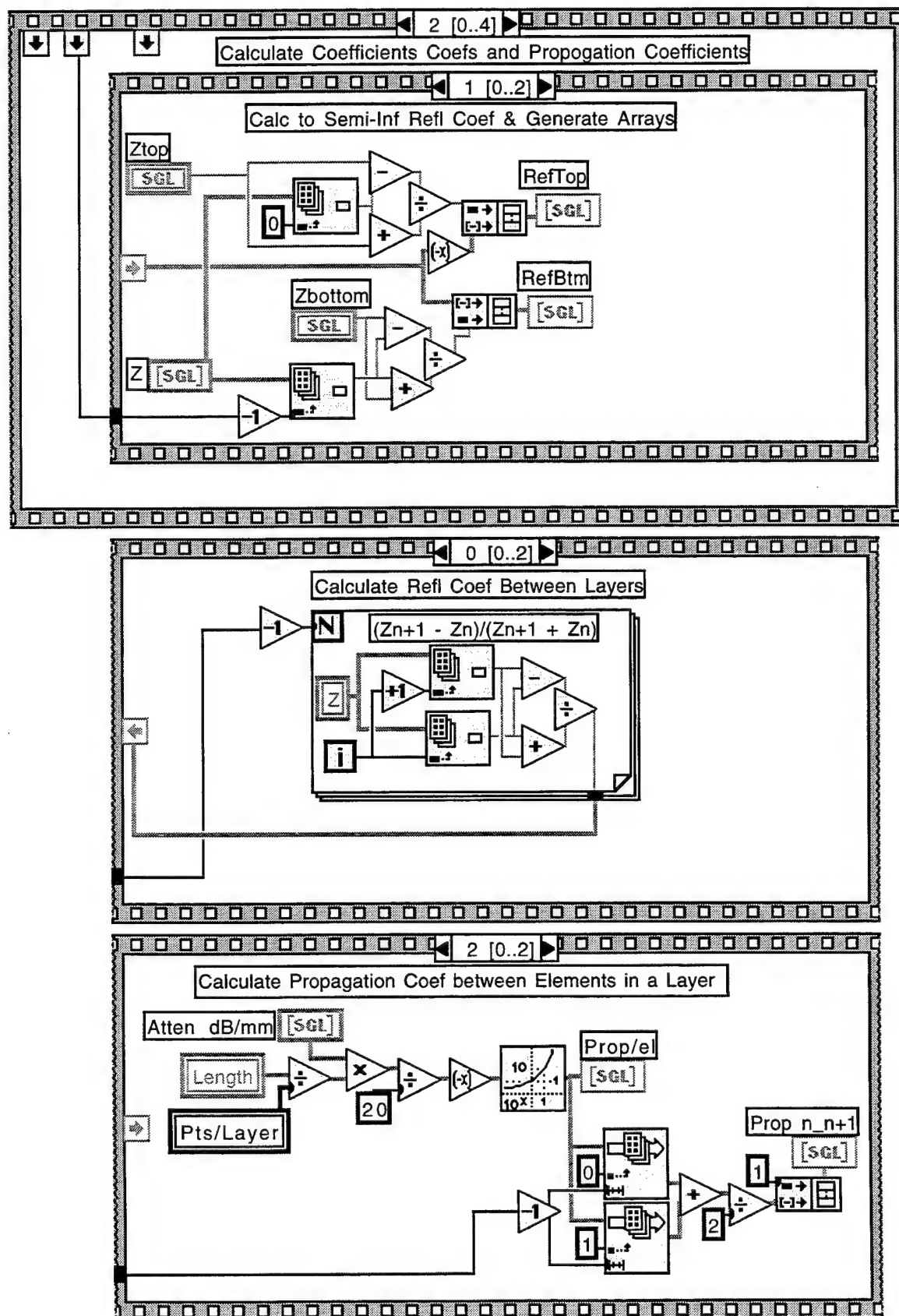




## 1D MultiLayer Model

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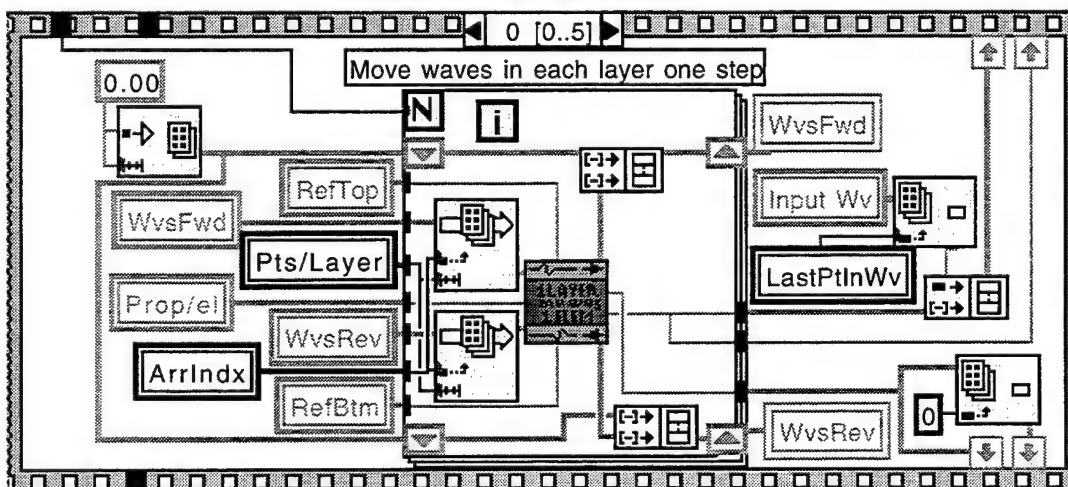
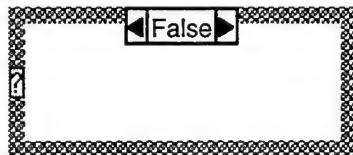
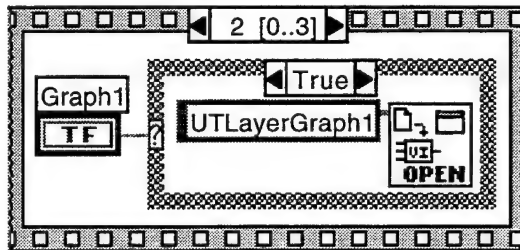
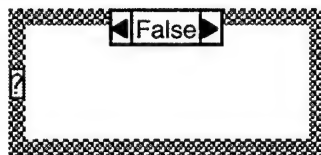
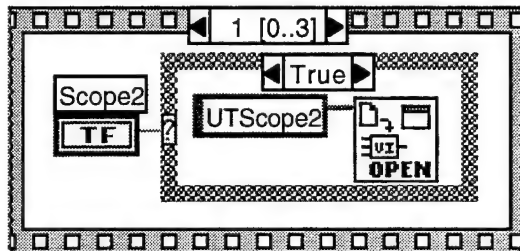
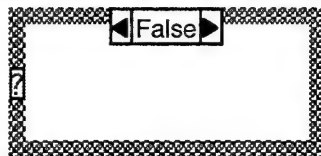
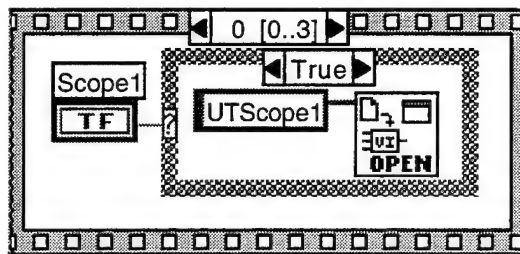




## 1D MultiLayer Model

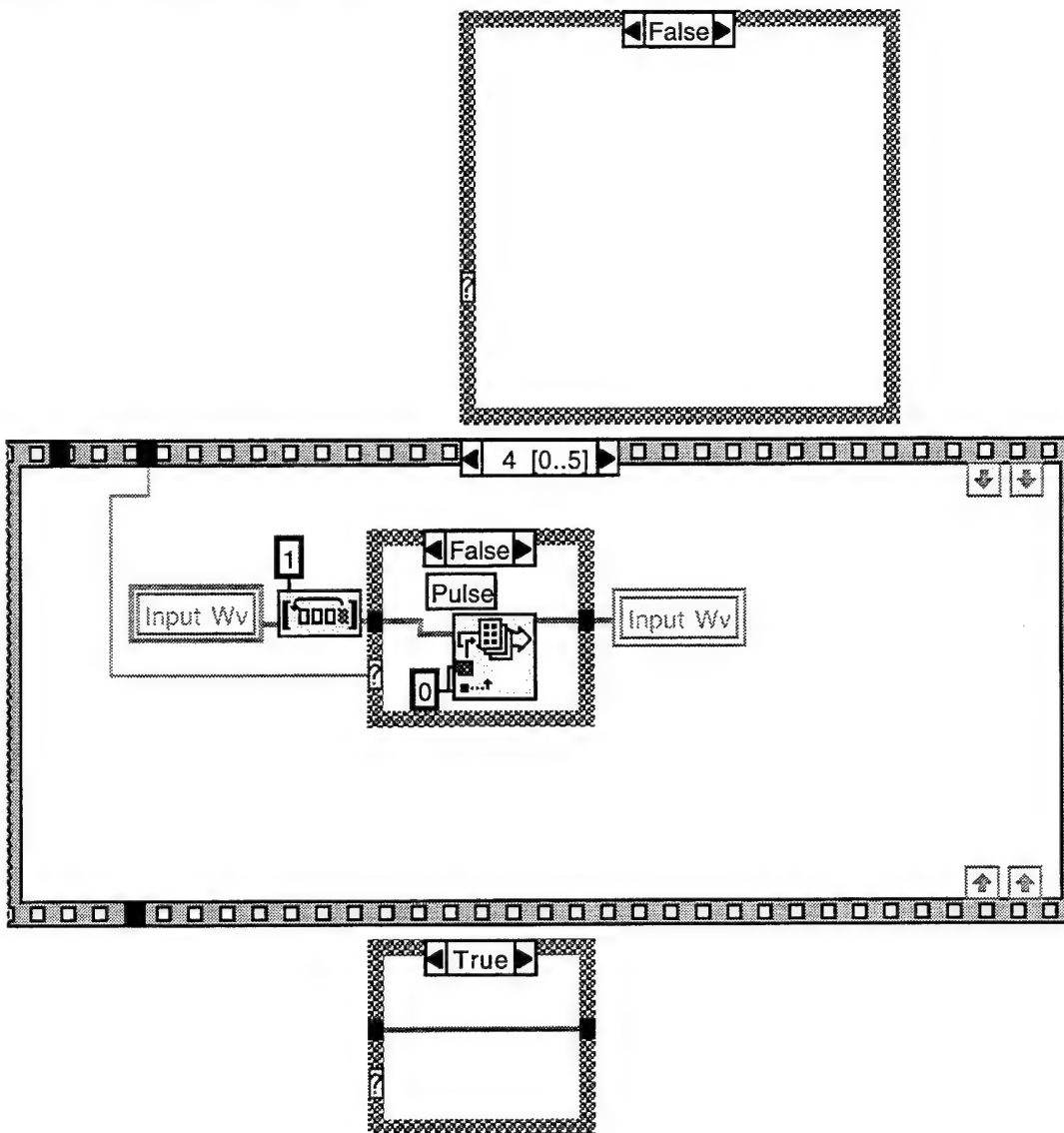
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Printed on 10/7/96 at 3:21 PM

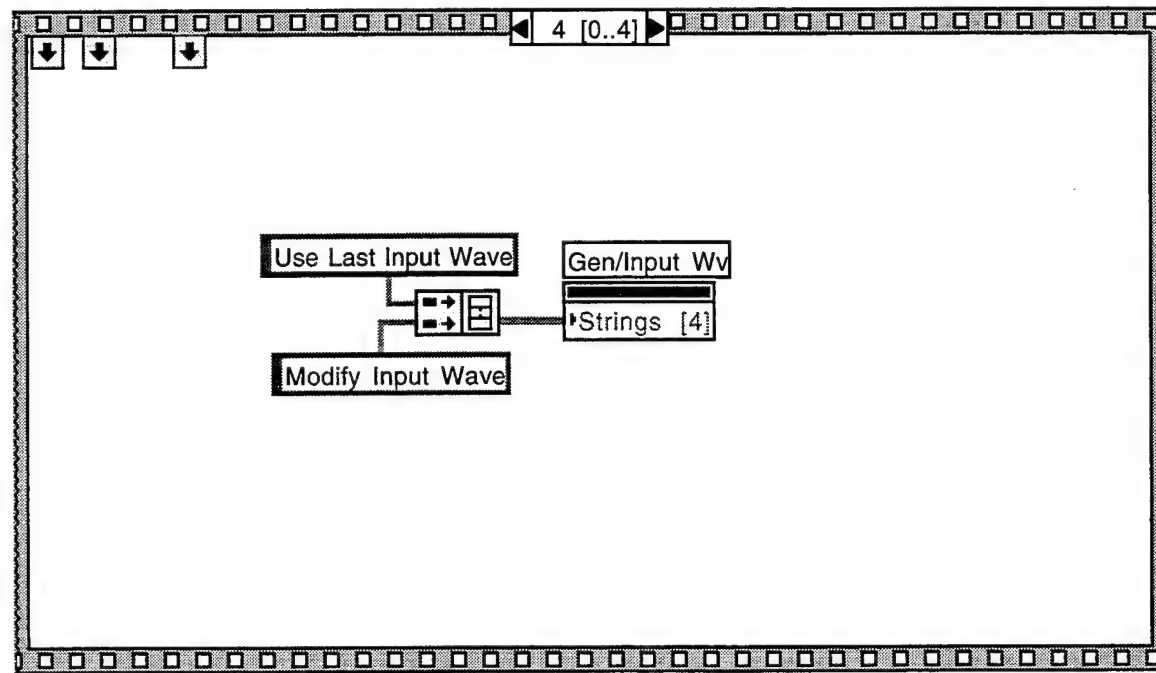




## 1D MultiLayer Model

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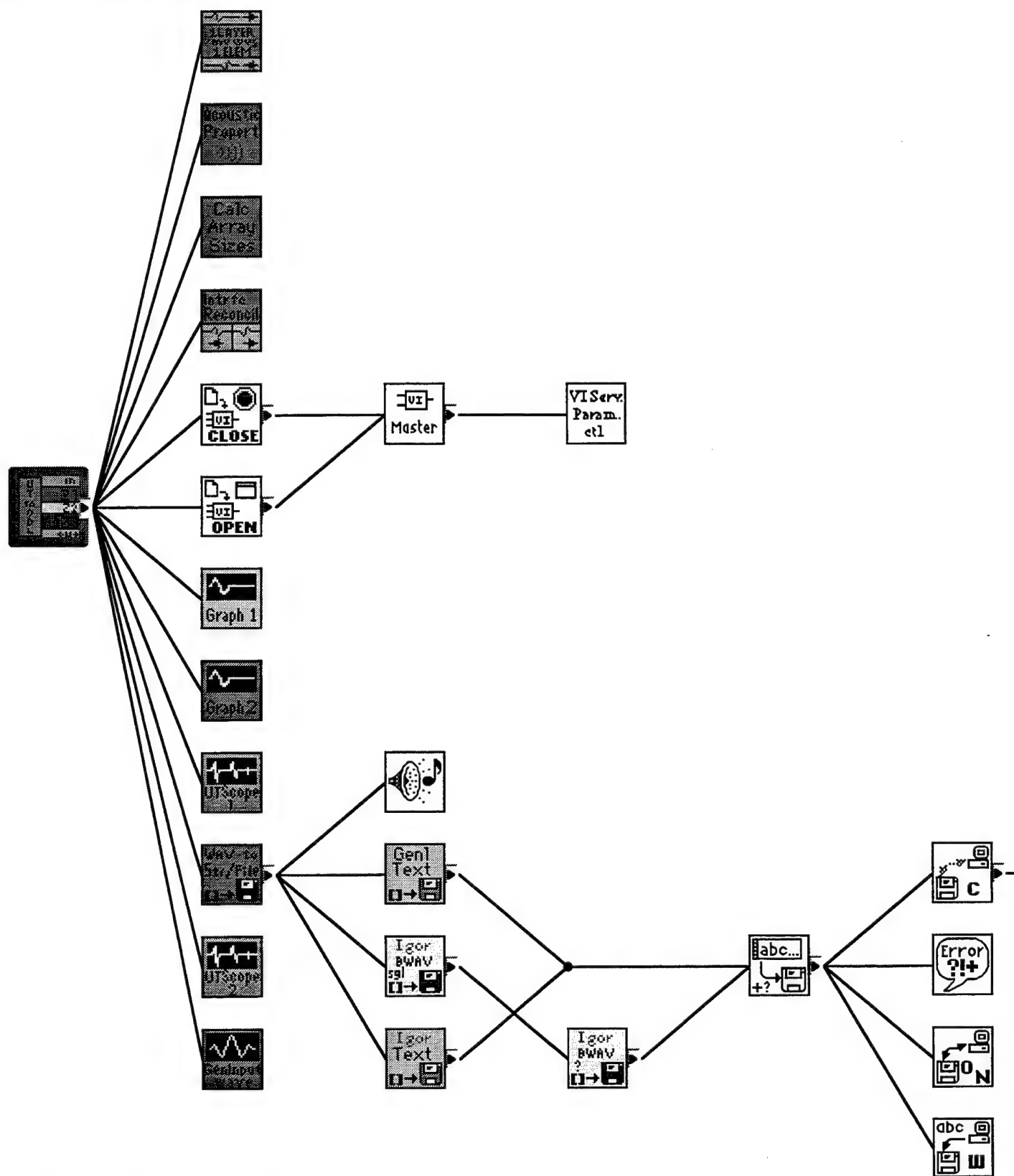
Position in Hierarchy



# 1D MultiLayer Model

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List of SubVIs



1D MultiLayer Model

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Find  
First  
Error





## 1D MultiLayer Model

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**Calc Arrays' Sizes**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Calc Arrays' Sizes

**1layer move wvs 1elem.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:1layer move wvs 1elem.vi

**Interface Reconcile.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Interface Reconcile.vi

**Global.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Global.vi

**UTLayerGraph1**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:UTLayerGraph1

**UTLayerGraph2**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:UTLayerGraph2

**UTScope1**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:UTScope1

**UTScope2**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:UTScope2

**Save #s to Strg/File**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Save #s to Strg/File

**Acoustic properties**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Acoustic properties

**WaveInput.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:WaveInput.vi

**Close Panel.vi**

Q540ppcHD:LabVIEW4ppc:vi.lib:Utility:victl.llb:Close Panel.vi

**Open Panel.vi**

Q540ppcHD:LabVIEW4ppc:vi.lib:Utility:victl.llb:Open Panel.vi

## History

"1D MultiLayer Model History"

Current Revision: 35

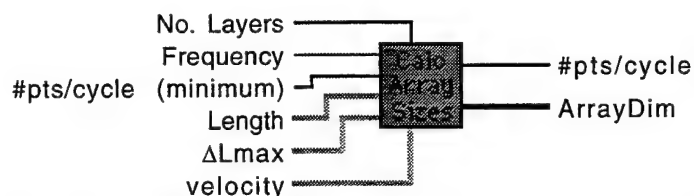


## Calc Arrays' Sizes

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Printed on 10/7/96 at 4:00 PM

## Connector Pane



Q540ppcHD:LabVIEW4ppc:UTModel2.Ilb:Calc Arrays' Sizes

Calculates array sizes for UT 1-D model of multiple layers of materials sandwiched between two semi-infinite media.

Jim Lhota July 1996

## Front Panel

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No. Layers	Frequency	#pts/cycle (minimum)	#pts/cycle
2	20.000 MHz	32	32
Length	velocity	ΔLmax	ArrayDim
6.0000 mm	6.30 mm/us	0.0500 mm	208
1.0000 mm	2.40 mm/us	0.0500 mm	208
1.8796 mm	5.84 mm/us	0.0500 mm	208
1.8796 mm	5.84 mm/us	0.0500 mm	208
1.8796 mm	5.84 mm/us	0.0500 mm	208

## Controls and Indicators

☐ U16 #pts/cycle (minimum)

☐ SGL Frequency

☐ [SGL] Length

☐ SGL L1

☐ [SGL] velocity

☐ SGL

☐ [SGL] ΔLmax

☐ SGL

☐ U8 No. Layers

☐ U16 #pts/cycle

☐ [U16] ArrayDim

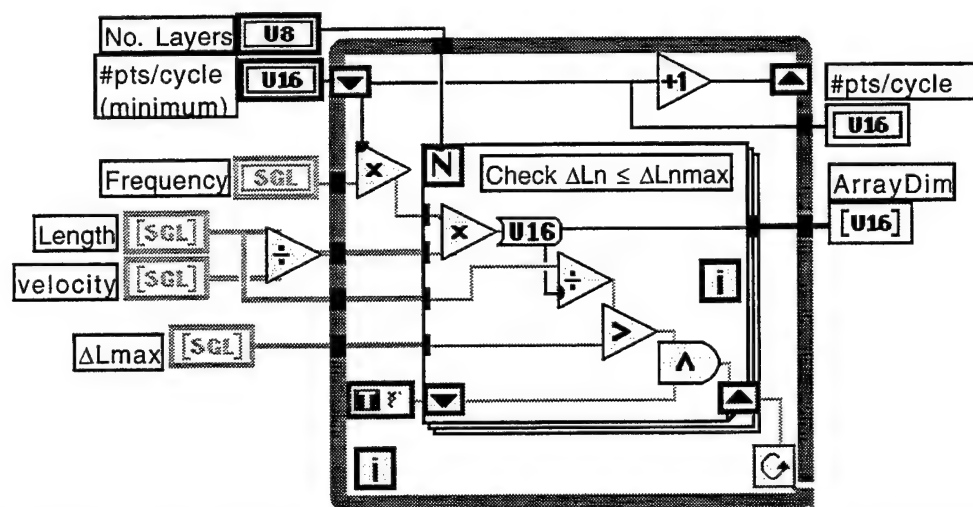
☐ U16

# Calc Arrays' Sizes

Last modified on 10/7/96 at 3:59 PM

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## Block Diagram



## Position in Hierarchy



## List of SubVIs

## History

"Calc Arrays' Sizes History"

Current Revision: 50

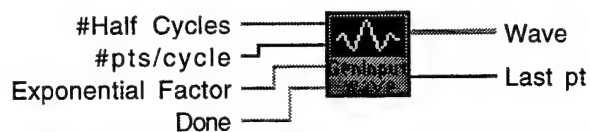


## WaveInput.vi

Last modified on 10/7/96 at 4:00 PM

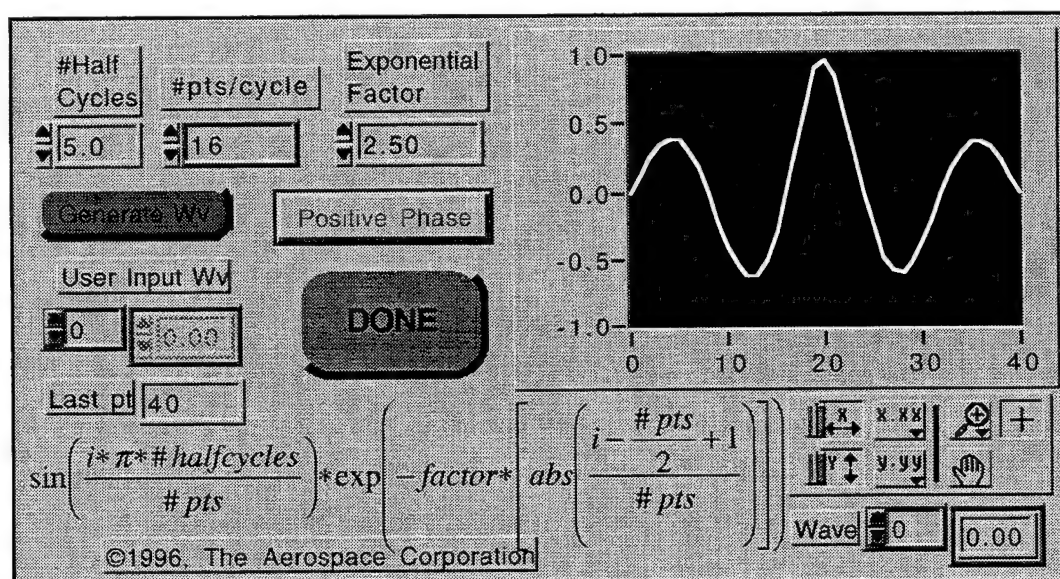
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## Connector Pane



Q540ppcHD:LabVIEW4ppc:UTModel2.IIb:WaveInput.vi

## Front Panel



## Controls and Indicators

- U16** #pts/cycle
- TF** Gen/Input Wv
- SGL** User Input Wv
- SGL**
- SGL** #Half Cycles
- SGL** Exponential Factor
- TF** phase
- TF** Done
- SGL**
- SGL** Wave
- SGL**
- U16** Last pt

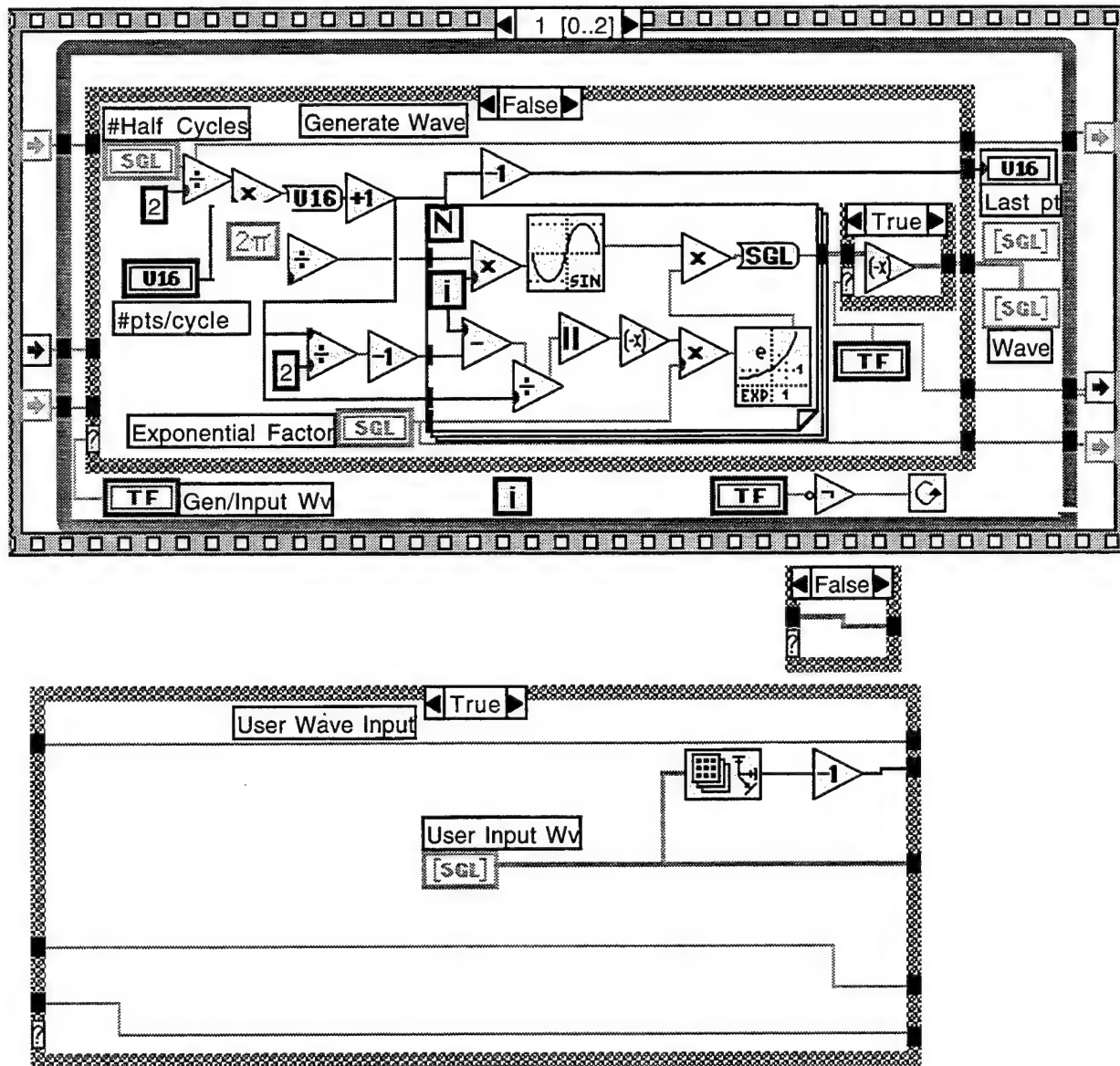


WaveInput.vi

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## Block Diagram

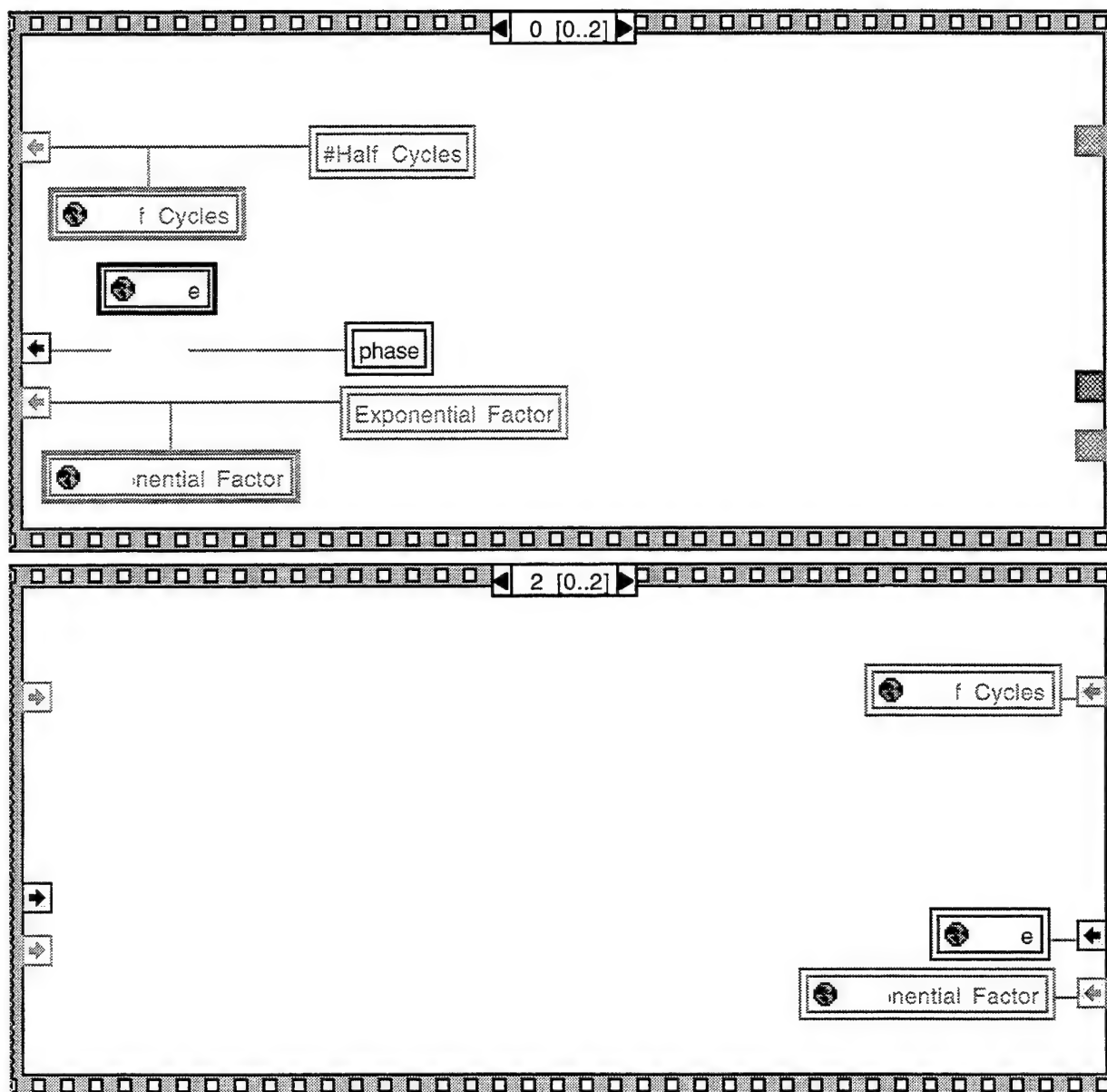




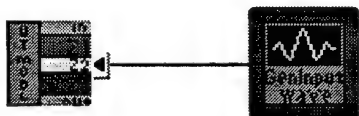
## WaveInput.vi

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## Position in Hierarchy



## List of SubVIs



## Global.vi

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Global.vi

## History



WaveInput.vi

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"WaveInput.vi History"

Current Revision: 40

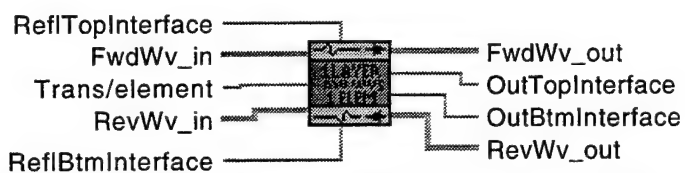


1layer move wvs 1elem.vi

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## Connector Pane



**Q540ppcHD:LabVIEW4ppc:UTModel2.llb:1layer move wvs 1elem.vi**

Inputs: Inputs from rt & lft interfaces, Afwd\_in(i), Arev\_in(i), R reflection coef for left and right interfaces, T=transmission per element of travel (i.e. 1-atten).

1.  $Afwd\_out(i) = T \cdot Afwd\_in(i-1) \quad i \neq 0;$   
 $Afwd\_out(0) = Rlft \cdot T \cdot Arev\_in(0) + InLftInterface$
2.  $Arev\_out(i) = T \cdot Arev\_in(i+1) \quad i \neq n;$   
 $Arev\_out(n) = Rlft \cdot T \cdot Afwd\_in(n) + InRtInterface$
3.  $OutLeftInterface = Arev\_in(0) - Rlft \cdot Arev\_in(0)$
4.  $OutRightInterface = Afwd\_in(n) - Rlft \cdot Afwd\_in(n)$

## Front Panel

## Controls and Indicators

- [SGL] FwdWv\_in
- [SGL]
- [SGL] RevWv\_in
- [SGL]
- [SGL] Trans/element
- [SGL] ReflTopInterface
- [SGL] ReflBtmInterface
- [SGL] FwdWv\_out
- [SGL]
- [SGL] RevWv\_out





1layer move wvs 1elem.vi

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[SGL]

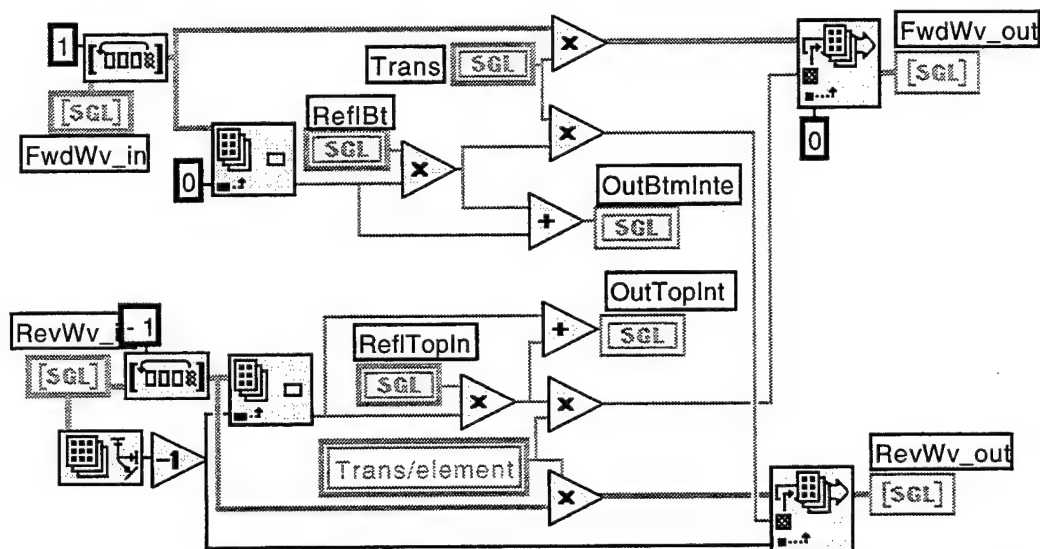
[SGL]

OutTopInterface

[SGL]

OutBtmInterface

## Block Diagram



## Position in Hierarchy



## List of SubVIs

## History

"1layer move wvs 1elem.vi History"

Current Revision: 48

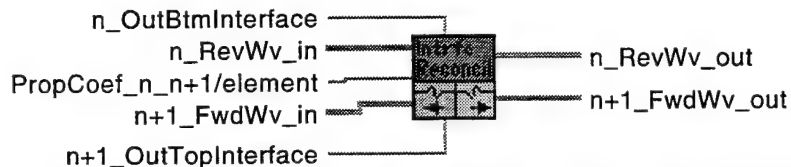


Interface Reconcile.vi

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Connector Pane

**Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Interface Reconcile.vi**

Inputs: Inputs from rt & lft interfaces, Afwd\_in(i), Arev\_in(i), R reflection coef for left and right interfaces, T=transmission per element of travel (i.e. 1-atten).

1.  $Afwd\_out(i) = T \cdot Afwd\_in(i-1) \quad i \neq 0;$   
 $Afwd\_out(0) = Rlft \cdot T \cdot Arev\_in(0) + InLftInterface$
2.  $Arev\_out(i) = T \cdot Arev(i+1) \quad i \neq n;$   
 $Arev\_out(n) = Rlft \cdot T \cdot Afwd(n) + InRtInterface$
3.  $OutLeftInterface = Arev\_in(0) - Rlft \cdot Arev\_in(0)$
4.  $OutRightInterface = Afwd\_in(n) - Rlft \cdot Afwd\_in(n)$

Front Panel

Controls and Indicators

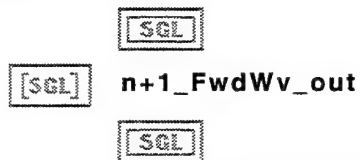
- [SGL] n+1\_FwdWv\_in
- [SGL]
- [SGL] n\_RevWv\_in
- [SGL]
- [SGL] PropCoef\_n\_n+1/element
- [SGL] n\_OutBtmInterface
- [SGL] n+1\_OutTopInterface
- [SGL] n\_RevWv\_out



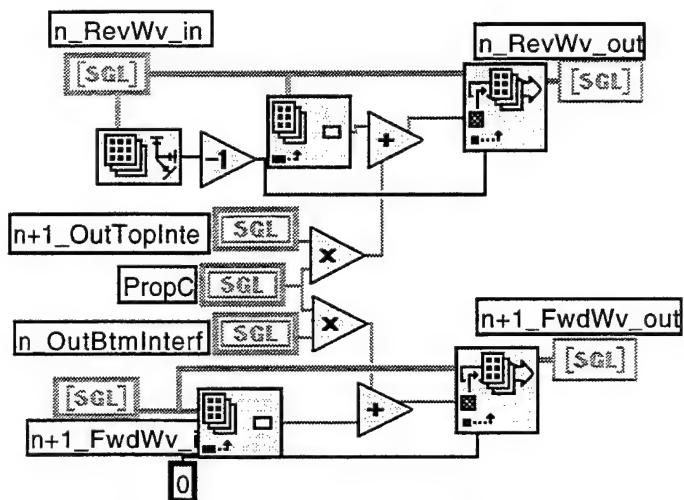
## Interface Reconcile.vi

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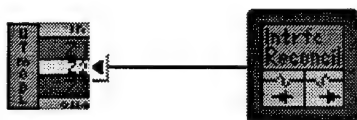
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## Block Diagram



## Position in Hierarchy



## List of SubVIs

## History

"Interface Reconcile.vi History"

Current Revision: 58



UTScope1

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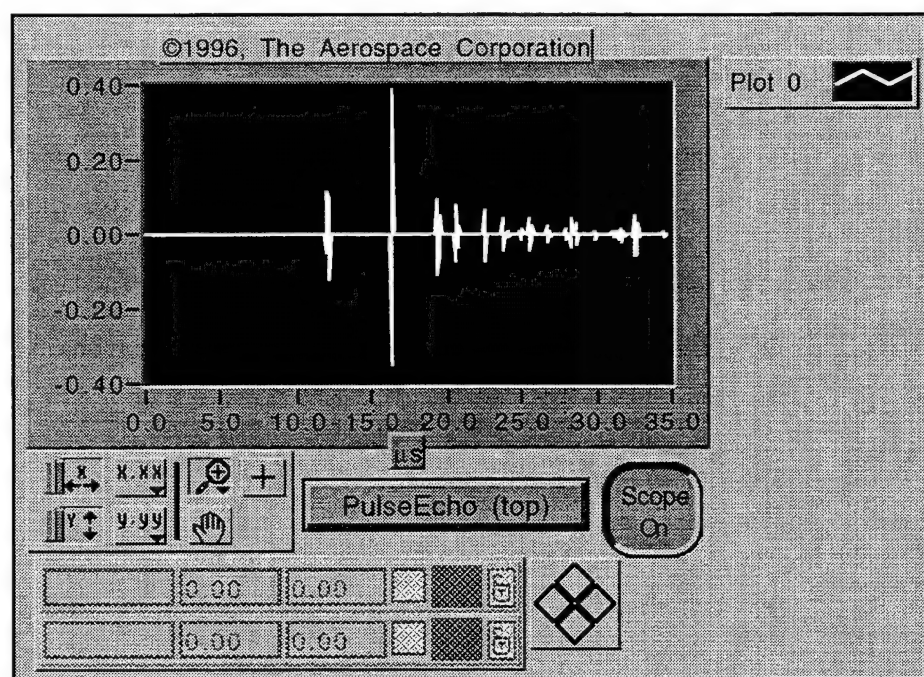
Connector Pane



Q540ppcHD:LabVIEW4ppc:UTModel2.IIb:UTScope1

Displays scope trace from ultrasonic models. V1.0 Jim Lhota, 1 Aug 1996.

Front Panel



Controls and Indicators

☐ **TF** Graph1

☐ **TF** stop

☐ **[SCL]**

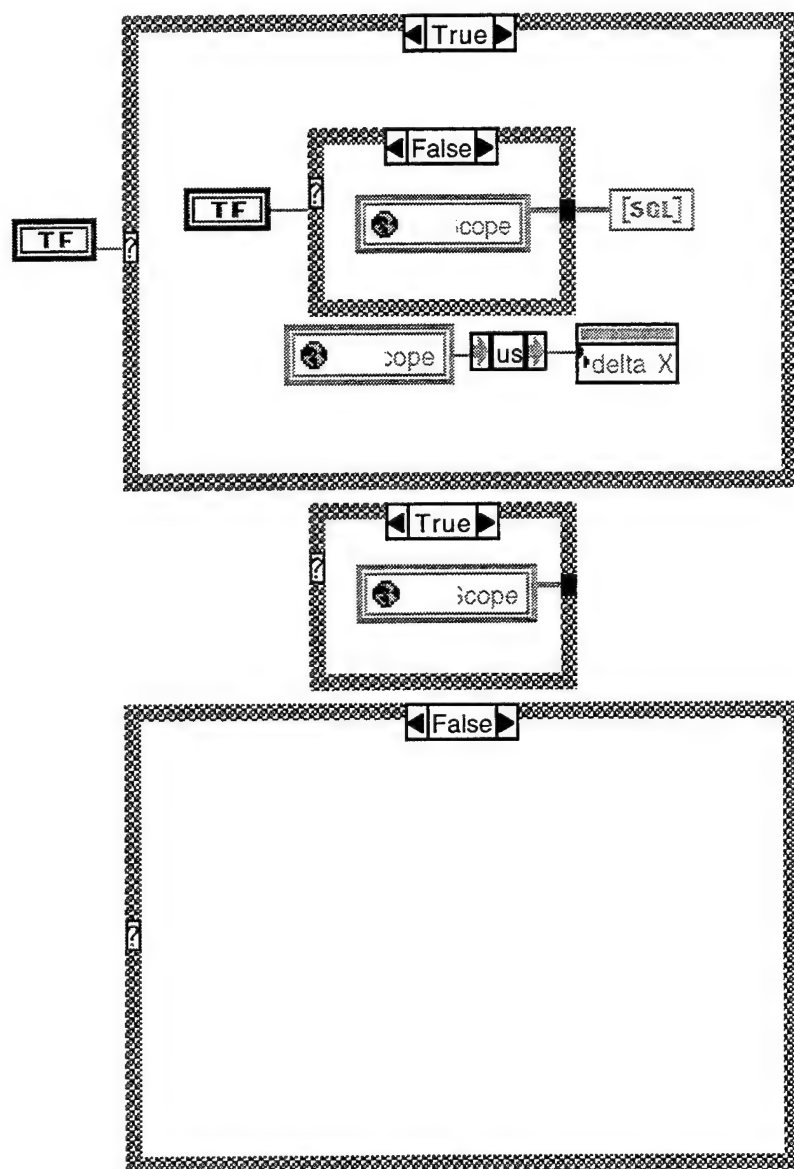


UTScope1

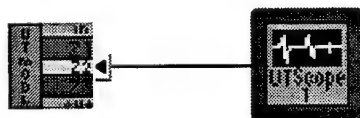
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## Block Diagram



## Position in Hierarchy



## List of SubVIs

**Global.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Global.vi

## History



UTScope1

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"UTScope1 History"

Current Revision: 32



UTLayerGraph1

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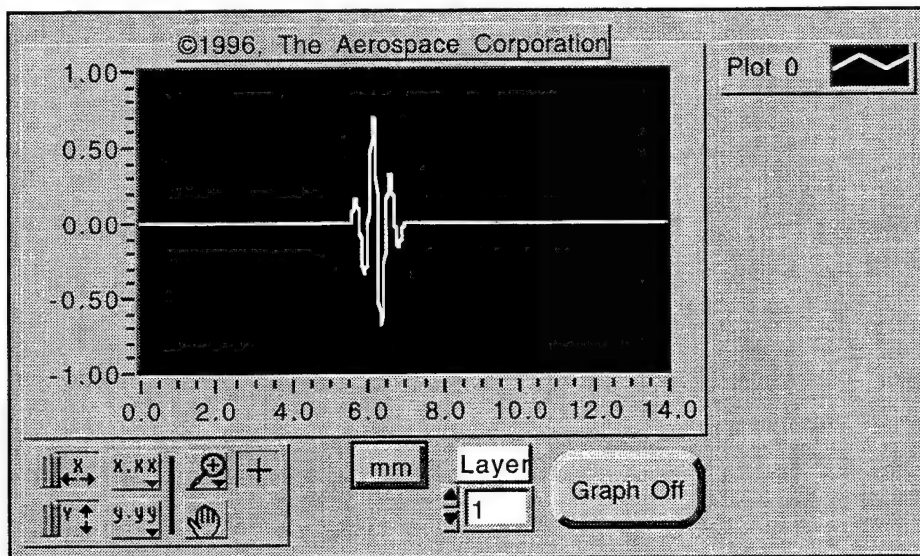
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Connector Pane

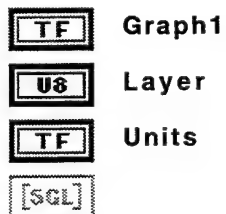


Q540ppcHD:LabVIEW4ppc:UTModel2.IIb:UTLayerGraph1

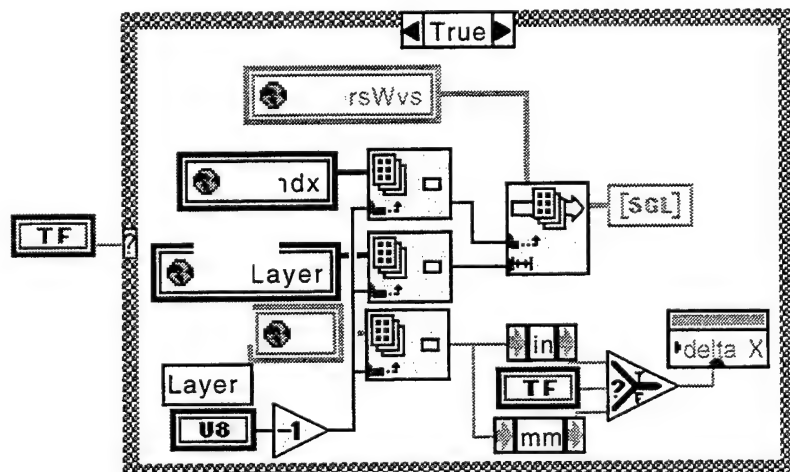
Front Panel



Controls and Indicators



Block Diagram

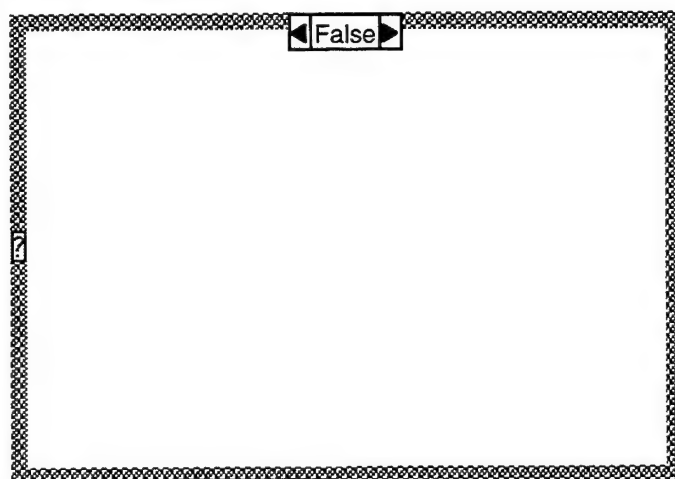




## UTLayerGraph1

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## Position in Hierarchy



## List of SubVIs

**Global.vi**

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Global.vi

## History

"UTLayerGraph1 History"

Current Revision: 34





Save #s to Strg/File  
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Connector Pane












#Layers



Q540ppcHD:LabVIEW4ppc:UTModel2.Ilb:Save #s to Strg/File

Front Panel

Controls and Indicators

-  SaveString
-  Done
-  SaveString copy
-  Wave to Save
-  File Format
-  #Layers
-  Layer# to Save
-  Comment
-   $\Delta t$  Scope
-  TopScope#s
-  BtmScope#s

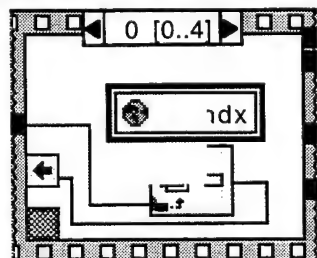
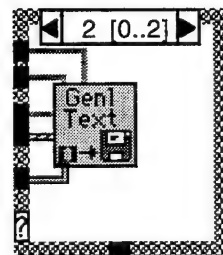
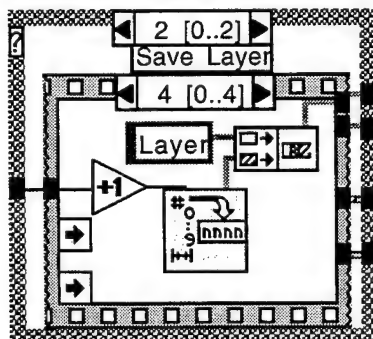
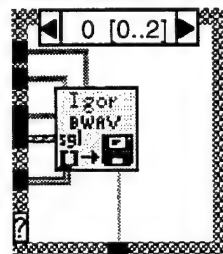
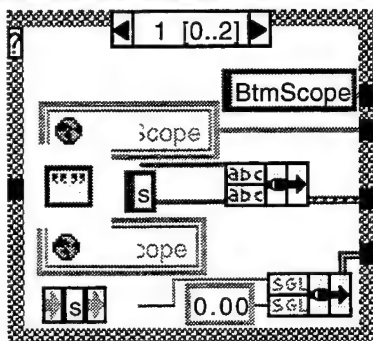
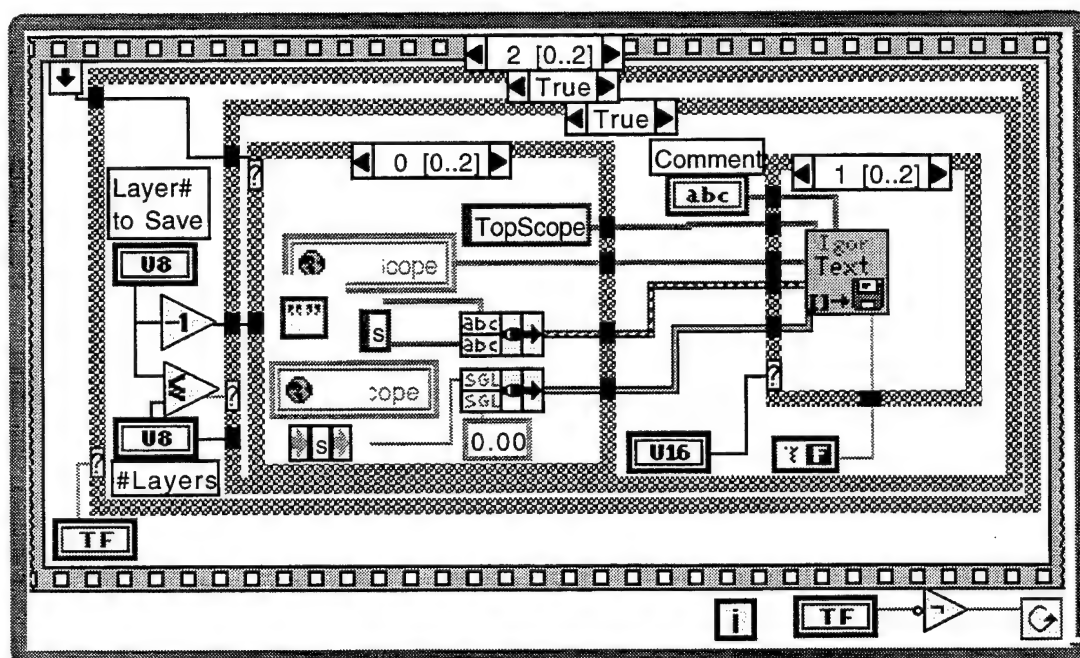


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# Block Diagram

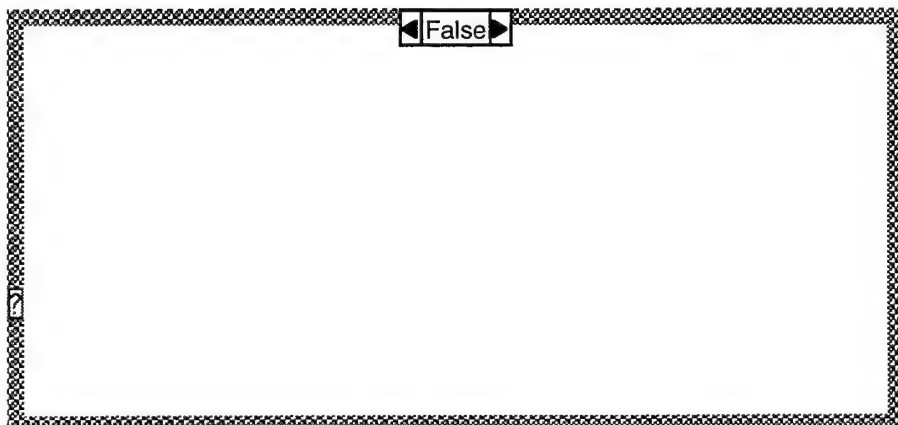
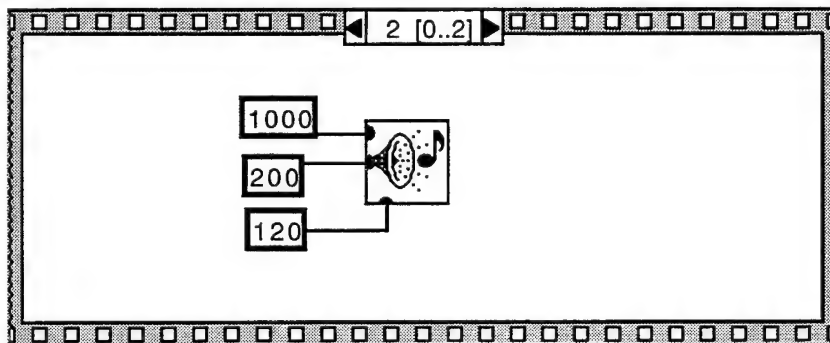
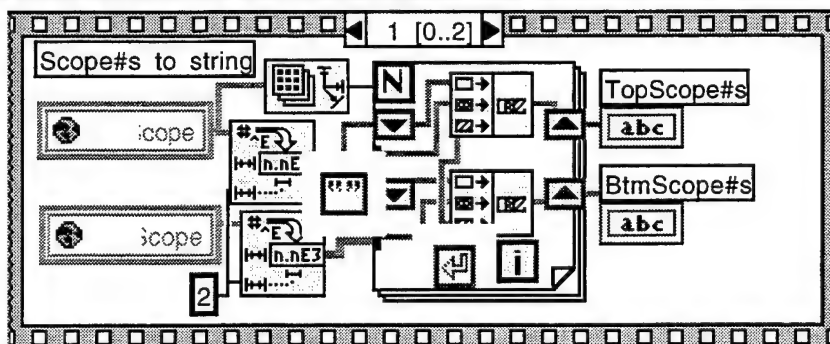
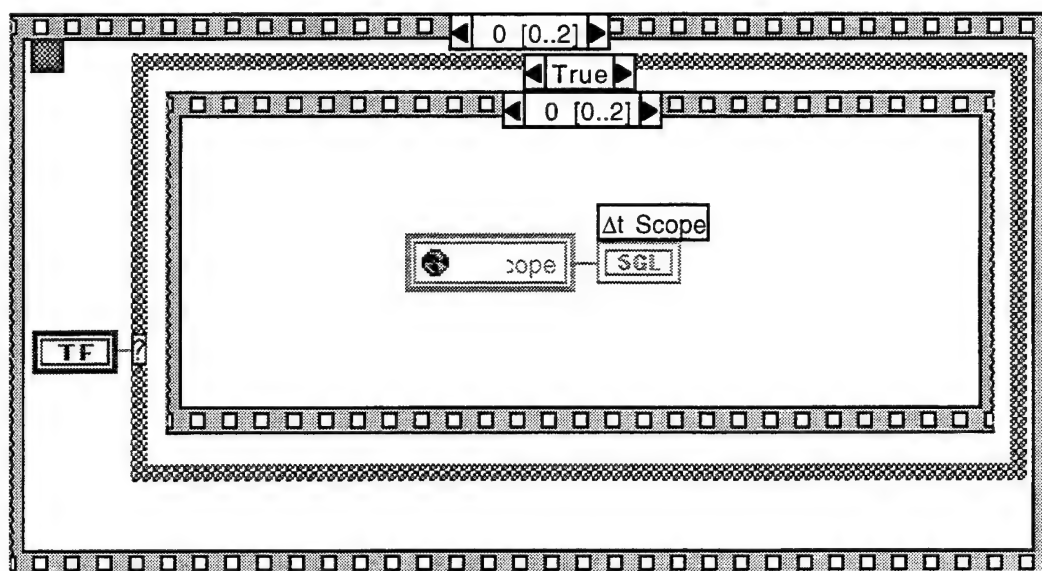




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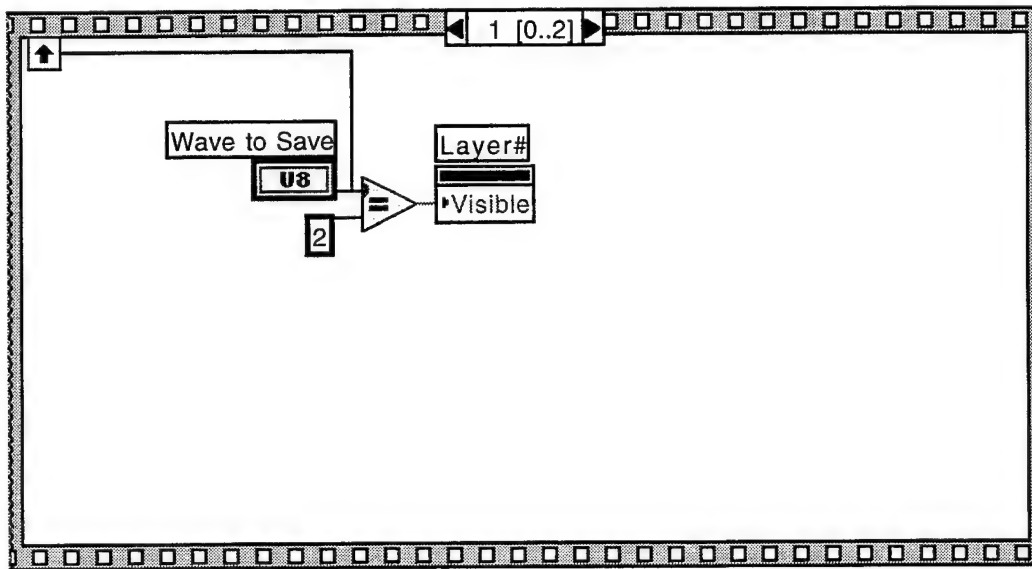




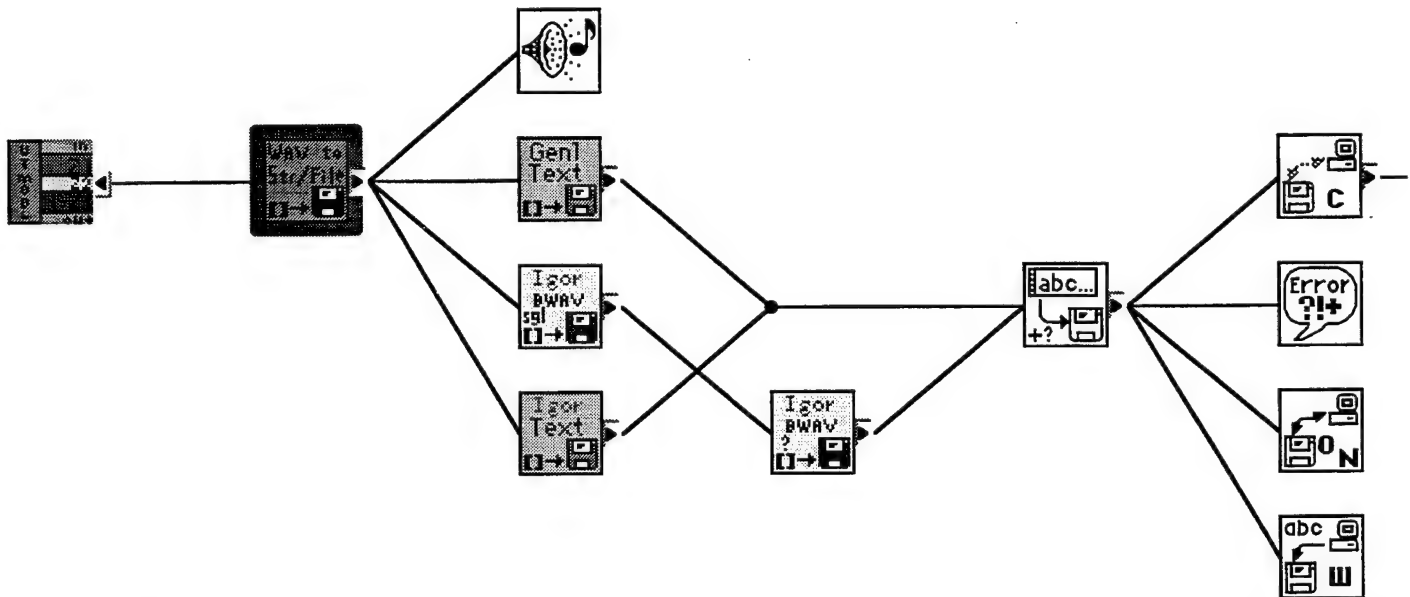
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Position in Hierarchy



List of SubVIs



#### Global.vi

Q540ppcHD:LabVIEW4ppc:UTModel2.llb:Global.vi



#### Beep.vi

Q540ppcHD:LabVIEW4ppc:vi.lib:Utility:system.llb:Beep.vi



#### Igor BRAW SGL to Igor Binary File

Q540ppcHD:LabVIEW4ppc:user.lib:Igor Binary I/O.llb:SGL to Igor Binary File



#### Igor Text

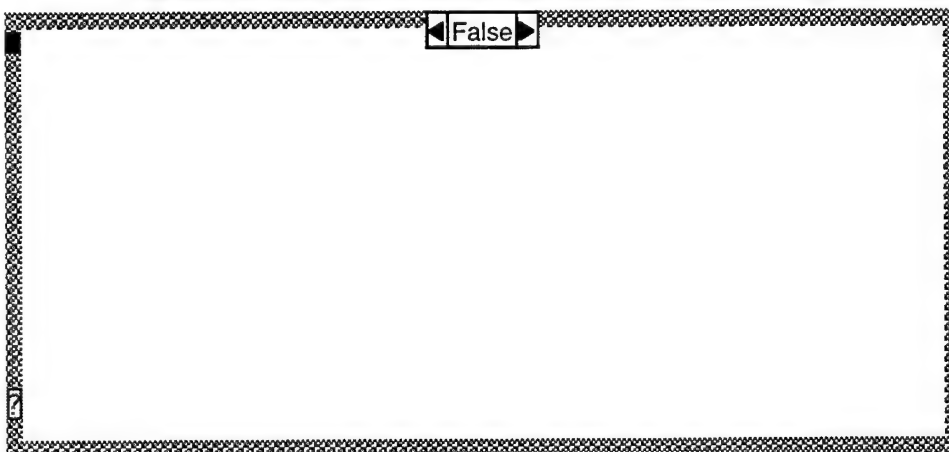
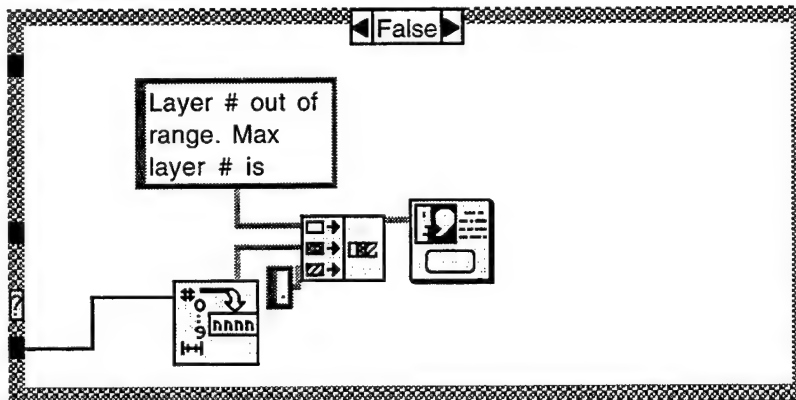
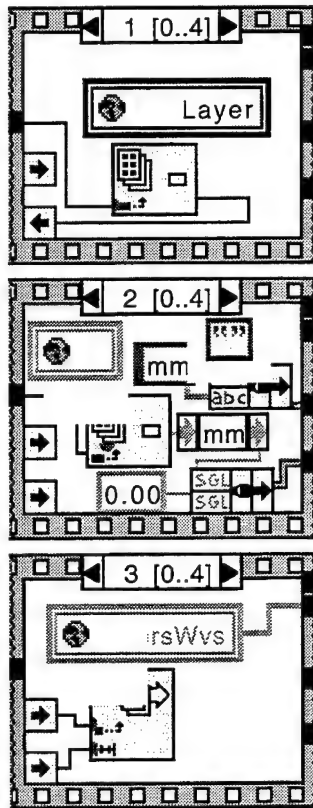
Q540ppcHD:LabVIEW4ppc:user.lib:Igor Binary I/O.llb:Sgl to Igor Text



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Find  
First  
Error



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### Sgl to Gen Text

Q540ppcHD:LabVIEW4ppc:user.lib:Igor Binary I/O.lib:Sgl to Gen Text

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## History

"Save #s to Strg/File History"

Current Revision: 32

Global.vi  
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## Connector Pane



Q540ppcHD:LabVIEW4ppc:UTModel2.IIb:Global.vi

## Front Panel

$\Delta L$	Pts/Layer	ArrIndx	LayersWvs	TopScope
0.0099 mm	1408	0	0.0000	0.00
0.0500 mm	208	208	0.0000	
0.0500 mm	208	208	0.0000	
0.0500 mm	208	208	0.0000	
0.0500 mm	208	208	0.0000	
0.0500 mm	208	208	0.0000	

#Half Cycles	Exponential Factor	Phase	$\Delta t$ Scope
6.0	4.50	Positive Phase	0.004255 us

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## Controls and Indicators

- [SGL]  $\Delta L$
- [SGL]
- [SGL] #Half Cycles
- [SGL] Exponential Factor
- [TF] Phase
- [SGL] LayersWvs
- [SGL]
- [U16] Pts/Layer
- [U16]
- [U16] ArrIndx
- [U16]
- [SGL] TopScope
- [SGL]
- [SGL] BtmScope
- [SGL]
- [SGL]  $\Delta t$  Scope



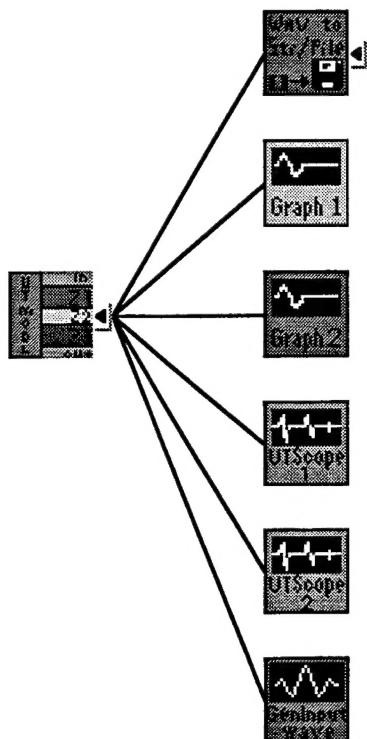
Global.vi

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## Block Diagram

## Position in Hierarchy



## List of SubVIs

## History

"Global.vi History"

Current Revision: 16

## TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

**Electronics Technology Center:** Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, Micro-Electro-Mechanical Systems (MEMS), and data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

**Mechanics and Materials Technology Center:** Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and composites; development and analysis of advanced materials processing and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; spacecraft structural mechanics, space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena; microengineering technology and microinstrument development.

**Space and Environment Technology Center:** Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.